Experiment.—To show that, for a given current passing through a given coil, the *rise in temperature is proportional to the time* during which the current passes, i.e. $\theta \propto t$. Use the same apparatus as before. Maintain a steady current in the circuit and take readings of the thermometer at appropriate equal intervals of time. The rate of rise of temperature should be approximately constant.

Before proceeding to the next paragraphs the student should become acquainted thoroughly, if not already so, with the quantities involved in any mechanical system.

Work is the overcoming of resistance, and is measured by the product of a force and the distance the point of application moves through in the direction of the force.

If the force is 1 dyne and the distance is 1 cm., then the work done is 1 erg, which is the fundamental unit of work.

The *Energy* of a body is measured by its capacity for doing work.

Power introduces the question of the time in which a certain amount of work can be performed.

$$\text{Hence } \textit{Power} = \text{Rate of doing Work}$$
$$= \frac{\textit{Work done (or Energy)}}{\textit{Time}}$$

HEAT UNITS.—When heat is generated in a conductor by the passage of a current, the electrical energy put into the conductor is converted into heat energy. The two principal units in terms of which heat is measured are, (1) the British Thermal Unit and (2) the calorie. These are defined as follows:

The *British Thermal Unit* (B.Th.U.) is the quantity of heat that is required to raise the temperature of 1 lb. of water through 1° F.

The *Calorie* is the quantity of heat that is required to raise the temperature of 1 gram of water through 1° C.

The *Grand Calorie* is a unit which is sometimes used by engineers. It is equal to 1,000 calories.

The *electrical unit of energy* is the **Joule**, which is *the energy developed in a resistance of* 1 *ohm when a current of* 1 *ampere flows through it for* 1 *second.*

$$\text{i.e. Joules} = I^2Rt = IVt = \frac{V^2t}{R}$$

where I, V, R and t are expressed in amps., volts, ohms and secs. respectively.

Further, if **all** the energy supplied in electrical form to any resistance is converted into the form of heat energy (H), then the equivalence between these two forms of energy may be written as

$$J.H. = I^2Rt$$

where H is expressed in *calories*, I^2Rt in *joules*, and J is a factor known as *Joule's Equivalent*. In a classical investigation extending over a long period of time, *Joule showed by a series of careful experiments that J was a constant and equal to* 4·19 (i.e. approximately 4·2).

i.e. 1 calorie is equivalent to 4.19 joules

or 1 joule=0·239 calorie.

Rewriting the above relation, $H = \frac{I^2Rt.}{4 \cdot 19}$ calories

But 1 lb. = 453·6 gms. and $1° F. = \frac{5°}{9} C.$

$\therefore$ 1 British Thermal Unit $= 453 \cdot 6 \times \frac{5}{9} = 252$ calories.

$$\text{Hence } H = \frac{I^2Rt}{4 \cdot 2 \times 252} \text{ B.Th.U.}$$

Electrical Units.—Now it has been stated (page 79) that the *Absolute Electro-magnetic Unit* (E.M.U.) *of Current* =10 *Amperes.*

$\therefore$ the *E.M.U. of Quantity*=10 *Coulombs*, where the coulomb is the practical unit of quantity, and *Coulombs*=*Amps.*×*Secs.* (see page 64).

The *E.M.U. of potential is defined as the P.D. between two points if* 1 *Erg of work is done in moving the E.M.U. of Quantity from one point to the other against the electrical force.*

The *E.M.U. of potential* $= \frac{Volt}{10^8}$, where the volt is the practical unit of electric potential.

$\therefore$ it follows that 1 joule $= IVt = (It)V$
$= (1 \text{ ampere} \times 1 \text{ sec.}) \times 1$ volt.
$= 1 \text{ coulomb} \times 1$ volt.
$= 10^{-1} \times 10^8$ ergs.

i.e. the Practical Unit of Work=1 *joule*=10^7 *ergs.*

Determination of the Number of Joules in a Calorie. *Experiment*.—A battery B (Fig. 105) is connected in series with an ammeter A, a rheostat R, and a coil H, the latter being immersed in water contained in a calorimeter. A voltmeter, V, is connected across the terminals of the coil as shown. When a current passes through the circuit the coil becomes heated and the temperature of the calorimeter and the contained water is raised. The initial and final temperatures after a time t secs. should be noted. If

m = mass of water contained in the calorimeter.
m_c = mass of copper calorimeter.
s_c = sp. heat of copper.

$\theta°$ C = rise in temperature of the calorimeter and contents. Then heat developed in the calorimeter $= (m + m_c s_c) \times \theta$ calories. Also, if

V = potential difference (volts) between the terminals of the coil.
I = current (amps.) flowing through the coil.

and t = time (secs.) during which the current flows in order that the temperature should be raised through $\theta°$ C.

$$\text{Then, heat developed} = \text{VI}t \text{ joules.}$$

$$\therefore (m + m_c s_c) \times \theta \text{ calories} = \text{VI}t \text{ joules.}$$

$$\text{and 1 calorie} = \frac{\text{VI}t}{(m + m_c s_c) \times \theta} \text{ joules.}$$

Example.—A current of 2·5 amperes is passed through a coil of wire whose resistance is 5·4 ohms for 5 minutes. Find the heat developed in the coil (1) in joules, and (2) in calories. (J = 4·2 joules/calorie.)

$$\begin{aligned} \text{Heat} &= \text{I}^2\text{R}t \text{ joules} \\ &= (2·5)^2 \times 5·4 \times 5 \times 60 \text{ joules} \\ &= 10130 \text{ joules} \\ &= \frac{10130}{4·2} \text{ calories} = 2412 \text{ calories.} \end{aligned}$$

Example.—A current of 4 amperes flows through a coil of 12·5 ohms resistance for 1 minute. Determine in joules the amount of heat developed in the coil. Determine also what current would generate twice as much heat in the coil in half the time.

$$\begin{aligned}\text{Heat} &= I^2Rt \text{ joules}\\ &= (4)^2 \times 12{\cdot}5 \times 60 \text{ joules}\\ &= 12{,}000 \text{ joules.}\end{aligned}$$

Let I_1 amperes be the current that would generate twice as much heat in the coil in half the time, i.e. in 30 seconds. Then

$$I_1^2 \times 12{\cdot}5 \times 30 = 12{,}000.$$

$$\therefore I_1^2 = \frac{12{,}000}{12{\cdot}5 \times 30} = 32{\cdot}0$$

$$\therefore I_1 = 5{\cdot}7 \text{ amperes.}$$

Example.—A coil of wire whose resistance is 50 ohms is completely immersed in 2 pints of water contained in a vessel. The ends of the coil are connected to a 200-volt supply mains and a current is allowed to pass through it for 5 minutes. If the initial temperature of the water is 59° F., what is the final temperature? (1 gallon of water weighs 10 lbs.)

Current flowing through the coil $= I = \frac{200}{50} = 4$ amps.

Let R = resistance of the coil.

Then, heat developed in the coil in 5 minutes $= I^2Rt$ joules

$$\begin{aligned}&= 4 \times 4 \times 50 \times 5 \times 60 \text{ joules}\\ &= 240{,}000 \text{ joules}\\ &= \frac{240{,}000}{4{\cdot}2 \times 252} \text{ B.Th.U.}\\ &= 226{\cdot}8 \text{ B.Th.U.}\end{aligned}$$

Weight of 2 pints of water $= 2{\cdot}5$ lbs.

Let the increase in the temperature of the water be t° F. Then the heat developed in the water $= 2{\cdot}5t$ B.Th.U.

$$\therefore 2{\cdot}5t = 226{\cdot}8$$

$$\text{or } t = 90{\cdot}7° \text{ F.}$$

$\therefore$ Final temperature of the water $= 59° + 90{\cdot}7° = 149{\cdot}7°$ F.

POWER.—It has been shown previously that

$$1 \text{ joule} = 10^7 \text{ ergs.}$$

$$\text{and } 1 \text{ calorie} = 4{\cdot}19 \text{ joules}$$

$$\text{Hence } 1 \text{ calorie} = 4{\cdot}19 \times 10^7 \text{ ergs.}$$

This quantity viz. $4{\cdot}19 \times 10^7$ *ergs/calorie* is known as the *Mechanical Equivalent of Heat.*

Now power is the rate of doing work.

$$\therefore \text{Electrical Power} = \frac{\text{Electrical Energy}}{\text{Time}}$$
$$= \frac{\text{Joules}}{\text{secs.}}$$
$$= \frac{\text{I.V.}t}{t}$$
$$= \text{IV}$$
$$= \text{Watts}$$

(If I is in amps. and V in volts.)

The practical unit of electrical power is the **Watt.**

1 Watt = 1 Joule per second.

The difference between a watt and a joule should be carefully noted.

A *joule* is a *quantity of energy.*

A *watt* is a *rate at which work is being done.*

If a current is flowing through a resistance and the P.D. in volts is multiplied by the current in amperes, the product gives the rate at which energy is consumed in watts,

or **Watts = Amps. × Volts.**

1 *Horse Power* (*H.P.*) = 550 *ft.-lb. per sec.*
= $550 \times 453{\cdot}6$ ft.-gm. per sec.
= $550 \times 453{\cdot}6 \times 30.48$ cm.-gm. per sec.
= $550 \times 453{\cdot}6 \times 981 \times 30.48$ cm. dyne per sec.

i.e. **1 H.P.** = 746×10^7 ergs. per sec.
= 746 joules per sec.
= **746 watts.**

Since 1 kilowatt = 1,000 watts.

Then 1 $H.P. = \frac{746}{1{,}000} = \frac{3}{4}$ *kilowatt* (approx.).

If work is done at the rate of one watt for one second, the work done is one watt-second or one joule. In one hour the work done will be one watt-hour, i.e. an equivalent to 3,600 joules.

For practical purposes the watt-hour is too small to be used as a unit. **The Board of Trade Unit** (B.O.T.) is the **kilowatt-hour.** It is equal to 1,000 watt-hours, or 3,600,000 joules, and is the unit by which electricity is bought and sold.

The kilowatt-hour can be defined as the quantity of energy supplied in any time by a current at such a pressure that the product of volts, amperes and hours equals 1,000.

Again, 1 H.P. $=\frac{3}{4}$ kilowatt (nearly).

$$\text{Hence 1 B.O.T.} = 1 \text{ kilowatt-hour}$$
$$= \frac{4}{3} \text{ H.P. hour}$$
$$= 1{\cdot}33 \textit{ H.P. hour}.$$

It is interesting to note that 1 unit of electricity will keep a 60-watt lamp alight for 16 hours, will boil about 14 pints of

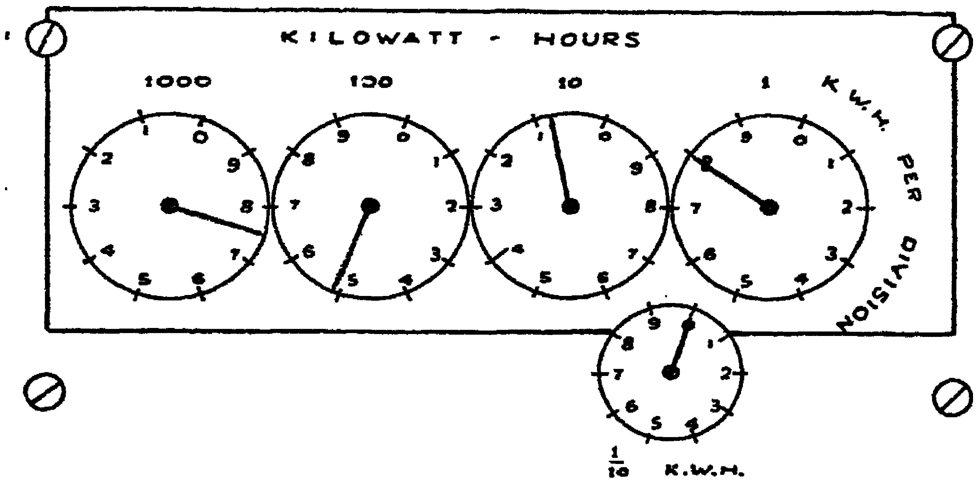


FIG. 106.

water, will drive a sewing machine for a day or operate an all-mains wireless set for about 15 hours. Fig. 106 shows the registering dial of the usual type of household electricity meter. The student should verify that the reading is 7508 units.

Example.—An electric kettle whose water equivalent is 100 gms. contains 900 gms. of water. When it is connected to a 210-volt main a current of 4 amperes flows through the heating element. If the original temperature of the water and kettle is 16° C. and the efficiency of the kettle is 80%, in what time will the water in the kettle be raised to the boiling point?

The water equivalent of the kettle being 100 gms. means that the quantity of heat required to raise the total mass of

the material of the kettle through 1° C. is the same as that necessary to raise 100 gms. of water through 1° C.

Let V volts be the potential difference across the mains, and I amperes the current through the circuit. Let t seconds be the required time.

$$\begin{aligned}\text{Total energy supplied} &= \text{watts} \times \text{time}\\ &= V \times I \times t \text{ joules}\\ &= 210 \times 4 \times t \text{ joules}\\ &= 840\,t \text{ joules}\\ &= \frac{840t}{4\cdot 2} \text{ calories}\\ &= 200t \text{ calories.}\end{aligned}$$

Since the efficiency of the kettle is 80%, the available

$$\begin{aligned}\text{energy} &= \frac{80}{100} \times 200t \text{ calories}\\ &= 160t \text{ calories.}\end{aligned}$$

This has to raise (100+900) gms. of water from 16° C. to 100° C. The heat required for this is equal to (1,000×84) calories.

$$\therefore 160t = 84{,}000.$$

$$\therefore t = \frac{84{,}000}{160} = 525 \text{ secs.}$$

$$= 8\tfrac{3}{4} \text{ mins.}$$

Example.—An electric kettle has an efficiency of 85%. What will be the cost if it is used to raise 1 quart of water from 16° C. to the boiling-point if the cost of electricity is $\frac{3}{4}$d. per B.O.T. unit? (One gallon of water weighs 10 lbs.)

1 quart of water weighs $\frac{10}{4}$ lbs $= \frac{10}{4} \times 453\cdot 6$ gms.

∴ Number of calories required to raise 1 quart of water from 16° C. to 100° C. $= \frac{10}{4} \times 453\cdot 6 \times (100-16)$

Now 1 calorie=4·19 joules.

∴ The electrical energy necessary to heat the water

$$= \frac{5}{2} \times 453\cdot 6 \times 84 \times 4\cdot 19 \text{ joules.}$$

But the efficiency of the kettle is 85%, i.e. 100 joules of electrical energy have to be supplied in order to obtain the

thermal equivalent of 85 joules. Hence the electrical energy which must be supplied to the kettle is

$$\frac{100}{85} \times \frac{5}{2} \times 453{\cdot}6 \times 84 \times 4{\cdot}19 \text{ joules}$$

$$= 4{\cdot}696 \times 10^5 \text{ joules or watt.-secs.}$$

$$= \frac{4{\cdot}696 \times 10^5}{3{,}600{,}000} \text{ kilowatt-hours}$$

and $\quad \textit{cost} = \frac{3}{4} \times \frac{4{\cdot}696}{36{\cdot}00} \text{ pence} = 0{\cdot}0978 \textit{ pence}.$

Hot-Wire Instruments.—The action of hot-wire ammeters and voltmeters depends upon the expansion of a fine wire when heated by an electric current, an effect which was illustrated by the first experiment described in this chapter. In practice the length of wire that can be incorporated in a commercial instrument is small, and so a device has to be adopted to magnify the sag.

Now if a current is passed through the wire AB (Fig. 107) the wire sags, and the silk thread XY, which is fixed to a hook at the mid point of AB, takes up the movement. This thread is wound at one point round a pulley P to the axle of which a pointer R is fixed. When any sag is produced by the current flowing in AB, it is taken up by the spring S and the pointer travels over the scale T. This scale is unevenly divided, but is graduated to read P.D. or current according to the purpose of the instrument. As in the case of the moving coil type, if the instrument is to be used as an ammeter the wire AB is shunted, or if as a voltmeter a high

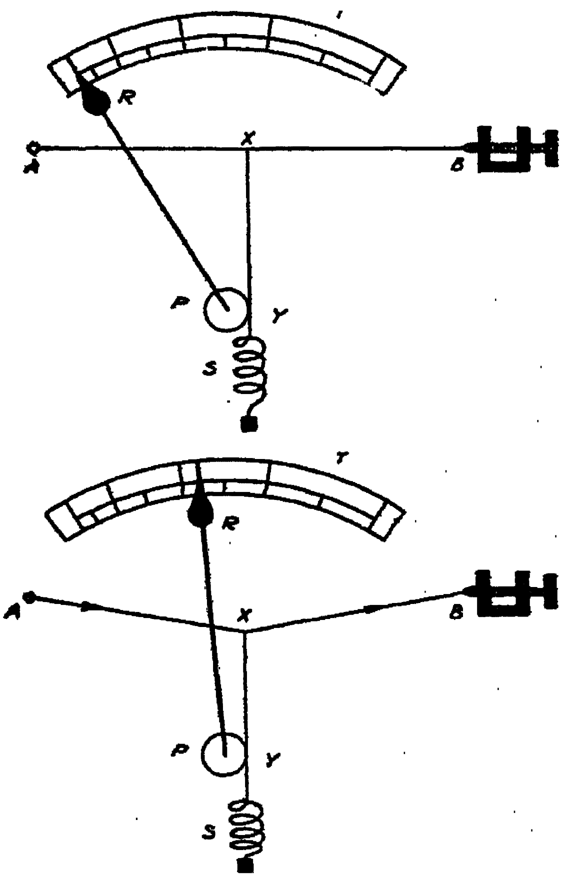


Fig. 107.

resistance is placed in series with AB. B is a zero adjusting screw.

Since the heat developed in AB and the expansion are both directly proportional to the square of the current passing through the wire, it follows that the scale divisions are not equal. Obviously also, the direction of the motion of the pointer across the scale is independent of the direction in which the current flows, so that a hot-wire instrument is equally suitable for direct and alternating currents (page 266). In practice it is usually calibrated by means of a direct current. This type of instrument possesses the further advantage that it is not influenced by magnetic fields. There may exist, however, a certain amount of lag in the reading of the instrument, as the wire takes time to reach its final temperature; also the zero is liable to change. It is very important that the current passed through the instrument does not exceed the maximum value intended, as the wire AB through which it passes is very thin and is liable to fuse with only a small overload of current. Since the wire has to withstand a high temperature it is usually made of platinum-iridium, of approximately 0.1 mm. diameter. Eddy current damping (page 268) is employed in these instruments by fixing a light metal disc to the spindle of the pointer, this disc moving between the poles of a permanent magnet.

POWER MEASUREMENT. *The Wattmeter.*—In a direct current circuit the power expended in any portion of resistance R may be found by determining the P.D. (in volts) across that portion, together with the current (in amps.) flowing through it. The power in watts will be given by the product of the ammeter and voltmeter readings, i.e. Watts=Volts×Amps. There is an instrument, however, in which this multiplication is performed automatically as it were, and it is known as a wattmeter.

The usual type of wattmeter is a dynamometer instrument and consists of moving and fixed coils. The fixed coils C (Fig. 108) are wound with thick wire and are connected in series to carry the main current, while the movable coil P contains a large number of turns of fine wire and thus constitutes a high resistance, R, say. This "pressure" or "voltage" coil is connected in series with a large non-inductive resistance X, and together they are placed in parallel with the portion of the circuit in which the power is to be measured.

It has been shown (page 77) that a current-carrying coil suitably suspended in a permanent magnetic field experiences a deflecting couple, which is proportional to the product of the field strength H and the current i. This result will obviously hold if the magnetic field is due not to a magnet but to a second current I passing in a suitably placed coil, and since this field H will be $\propto$I (page 79) it is evident that the deflecting couple is $\propto i$I.

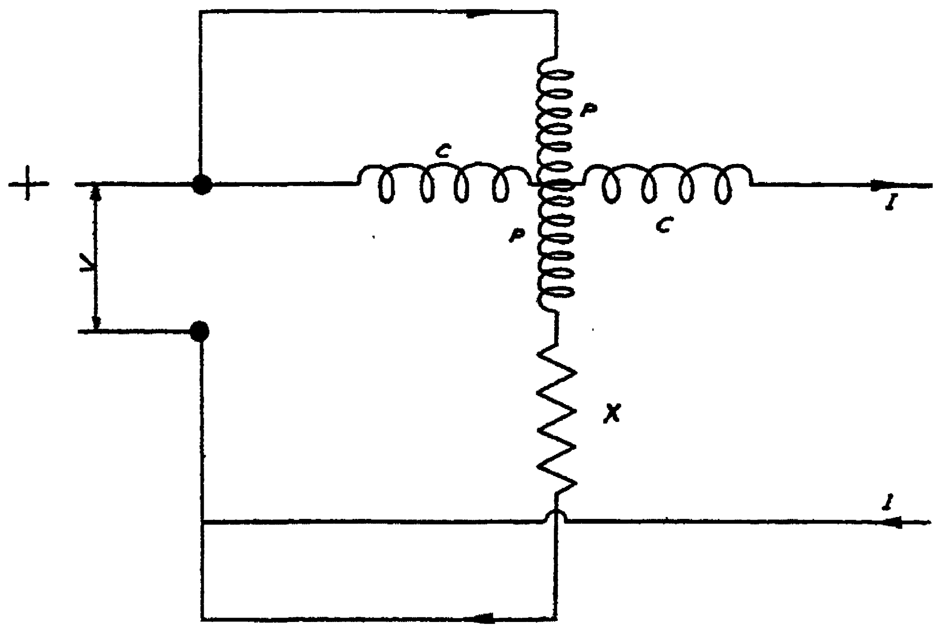


FIG. 108.

Now if V be the P.D. of the supply then the current through the pressure coil is

$$i = \mathrm{V}/(\mathrm{R}+\mathrm{X}).$$

Hence the deflecting couple is $\propto i\mathrm{I}$

$$\propto \mathrm{VI}/(\mathrm{R}+\mathrm{X})$$

$\propto$VI since (R+X) is constant. But VI is the power supplied to the portion of the circuit under consideration, and therefore the deflecting couple is proportional to the power supplied.

Furthermore, it is obvious that the couple will be independent of the direction of the current in the external circuit, and hence the wattmeter may be used for power measurements on alternating current circuits.

QUESTIONS.

1. What are the laws of the "heating effect of an electric current"? Describe briefly how you would verify them experimentally.

2. Define the calorie and the British Thermal Unit. Determine the number of calories in a British Thermal Unit. (1 lb. = 453·6 gms.)

3. How many calories of heat are developed in half an hour in an electric kettle which takes 6 amps. at 110 volts?

4. A coil of resistance 20 ohms is immersed in a calorimeter containing 180 gms. of water and a current of 0·5 ampere is passed through the coil for five minutes. Calculate the rise in temperature of the water (1 calorie = 4·2 joules.)

5. Define the "watt."

If the charge for electrical energy is 2d. a unit, find the cost of running (*a*) ten 60 watt lamps continuously for 12 hours, and (*b*) five 100 watt lamps continuously for 10 hours.

6. What is the resistance of a 60 watt lamp which is to be used on a 110 volt circuit?

What would it cost to run 10 such lamps in parallel for three hours if the price of electricity is 6d. per Kilowatt-hour?

7. Define: Ampere, Ohm, and Volt.

A 200 volt electric light installation consists of the following: ten lamps each 100 watts, eight lamps each 60 watts, and eight lamps each 40 watts, all connected in parallel.

If all the lamps are switched on, calculate: (*a*) the current taken from the mains; (*b*) the cost of lighting for five hours if the price of electricity is 2d. per B.O.T. unit. (U.E.I., S1, 1932.)

8. If the joint resistance of two coils connected in parallel is 1 ohm, and one of them alone has a resistance of 3 ohms, find the resistance of the other. Compare the heat produced respectively in the two coils when connected in parallel. (C. & G., 1918.)

9. An electric kettle used on a 210 volt supply takes a current of 1·5 amps. If the efficiency of the kettle is 85%, how long will it take to raise the temperature of a kilogram of water from 16 deg. C. to the boiling point? (1 cal. = 4·2 joules.)

10. An electric radiator when used on a 210 volt circuit takes a steady current of 7·5 amps. How many (1) B.O.T. units and (2) British Thermal Units will be consumed by the radiator in one hour? (1 watt = 0·00096 B.Th.U. per second.)

11. The efficiency of an electric kettle is 85%. What will be the cost of using the kettle to raise two pints of water from 50 deg. F. to the boiling point, if the cost of electrical energy is 1½d. per B.O.T. unit? (1 gallon of water weighs ten pounds.)

CHAPTER VIII

CHEMICAL EFFECTS OF THE CURRENT

Passage of the Current through Liquids.—Some liquids, e.g. pure distilled water, ether, and paraffin oil do not conduct electricity. Mercury, which is the only metal which is a liquid at ordinary temperatures, conducts electricity in exactly the same manner as copper, iron, and other metals do. It becomes heated, but it undergoes no chemical change. Solutions of most of the salts, however, as well as some acids when diluted, conduct electricity and are decomposed during the passage of the current. Faraday applied the term *electrolysis* to the process of decomposition, and the liquids themselves were known as **electrolytes.** The terminals by which the current enters and leaves the liquid were referred to as *electrodes*. That by which the current enters the liquid was called the **anode,** and that by which it leaves it was called the **cathode.** This nomenclature of Faraday is still retained.

Electrolysis of Acidulated Water.—It has already been stated that pure water is a non-conductor of electricity. If, however, a little dilute acid is added to it a current will flow through it and oxygen gas is evolved at one electrode and hydrogen gas at the other.

Experiment.—Pour some water to which a little dilute sulphuric acid has been added into a *voltameter* (V in Fig. 109 also Fig. 110). Join the terminals to which the electrodes are attached to a battery, rheostat, and key which are connected

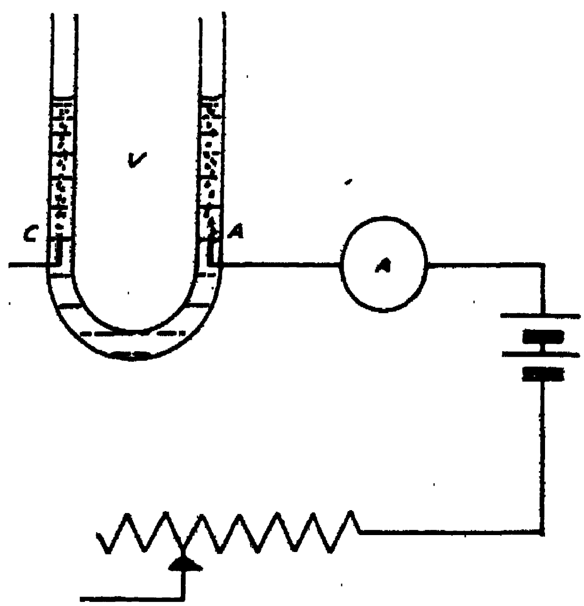


Fig. 109.

in series as shown. When a current passes through the circuit, the liquid is decomposed and hydrogen gas is given off at the cathode (C), and oxygen gas at the anode (A). It is found that the hydrogen collects at twice the rate that the oxygen does. The action is represented by the equation

$$2\ H_2O = 2\ H_2 + O_2.$$

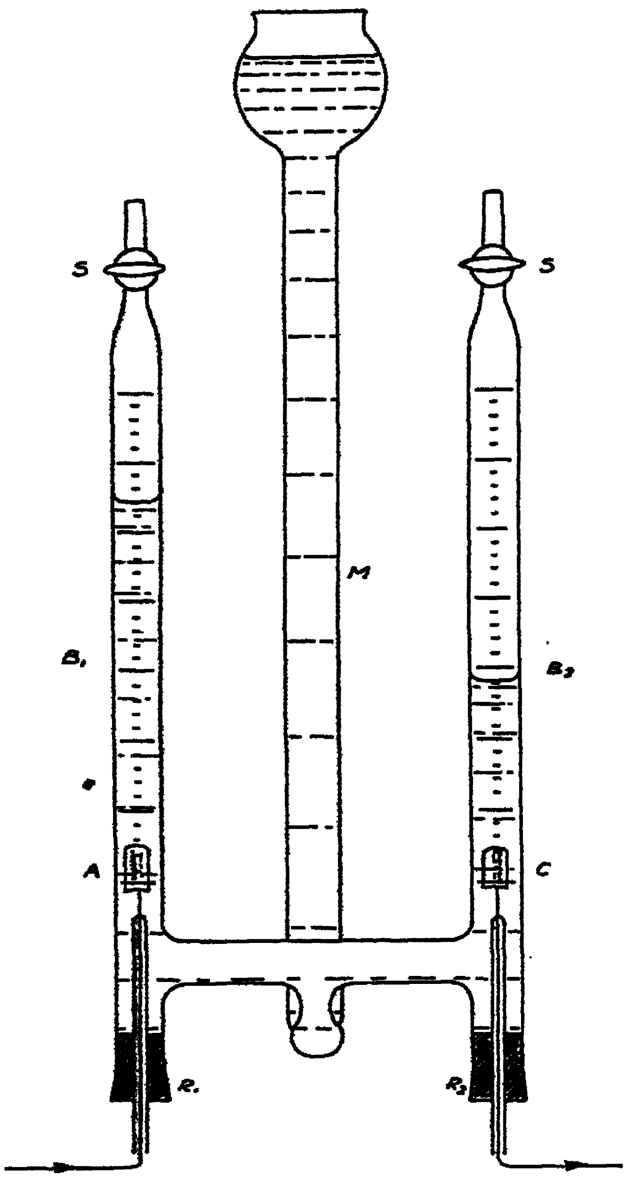


FIG. 110.

The decomposition of acidified water by electrolysis may be utilised to determine the polarity of the Direct Current Lighting Mains. For this purpose two insulated leads are taken from the plug points and the bared ends are placed at a suitable distance apart in a vessel containing ordinary tap water, which is sufficiently conducting. On switching-on the current, hydrogen gas is immediately given off at the cathode lead (which is connected, of course, to the —ve side of the mains), the oxygen liberated at the anode lead merely oxidising the copper wire.

THE DISSOCIATION OR IONIC THEORY OF ELECTROLYSIS.—This was first suggested by Faraday and was later, in 1887, more fully developed by a Swedish scientist, Arrhenius. According to this theory, a salt in solution consists not only of molecules of the salt but also of dissociated molecules. Thus, if common salt (sodium chloride, NaCl) is dissolved in water some of the molecules are supposed to split up into their components, thus

$$NaCl \rightleftharpoons \overset{+}{Na} + \overset{-}{Cl}$$

The sodium atom is positively charged and the chlorine atom is negatively charged. These charged atoms are called **ions**, and it is important to notice that the properties of the ions are not the same as those of the uncharged atoms. In the case of sodium, for example, this metal in the ordinary way attacks water, but the sodium ion exists in a free state in water without any action taking place. These +vely and −vely charged ions wander about in the solution and collide with each other and with the molecules of the solute (i.e. the dissolved salt), so that some oppositely charged ions will

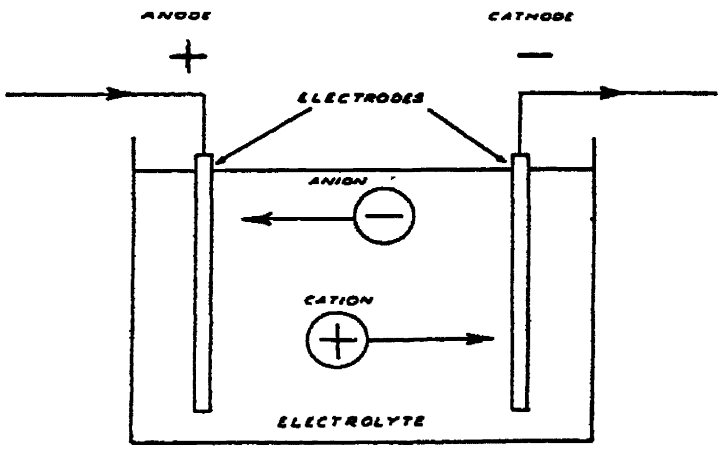


FIG. 111.

recombine, i.e. associate, while fresh molecules will be **dissociated.** Hence the use of oppositely directed arrows in the above equation. It is obvious that the weaker the solution the smaller is the chance of a collision, and therefore the greater is the *percentage* of molecules ironised. The application of an e.m.f. to the *electrodes* merely *directs* the ions towards the electrodes.

It is evident that the electrical conductivity of an electrolyte will depend upon the *degree of ionisation* of the salt.

In the electrolysis of acidulated water or *dilute* sulphuric acid $\left(\overset{+}{H_2}\overset{-}{SO_4}\right)$ described above (see Fig. 111), the positively charged hydrogen ion which travels down in the conventional direction of the current is called the *cation*. When it reaches the cathode it loses its charge and collects as ordinary hydrogen gas in the tube. The negatively charged (SO_4)

ion which travels up against the current is called the *anion*. This is not given off as (SO_4) at the anode because a secondary reaction takes places here. The ion, on losing its charge, reacts on the water and produces sulphuric acid and oxygen. The action is represented by the equation

$$2\ SO_4+2\ H_2O=2\ H_2SO_4+O_2.$$

The liberated oxygen gas collects in the tube of the voltameter.

If a current is passed through a solution of caustic soda $\left(\text{sodium hydroxide, } \overset{+}{Na}\ \overset{-}{OH}\right)$, the sodium ions which are set free at the cathode lose their charge and act on the water with the result that sodium hydroxide is reformed and hydrogen is liberated. The reaction is represented by the equation

$$2\ Na+2\ H_2O=2\ NaOH+H_2.$$

The ($\overset{-}{OH}$) ion liberated at the anode loses its charge and action takes place between it and the water. This is represented by the equation

$$4\ (OH)+2\ H_2O=4\ H_2O+O_2$$

Hydrogen and oxygen are likewise given off at the cathode and anode respectively if a current is passed through a solution of potassium hydroxide, KOH. The final products are thus the same as those obtained when acidulated water is electrolysed.

The metals sodium or potassium can, however, be obtained from caustic soda or caustic potash by first fusing the appropriate salt and passing a current through it. In 1807, *Sir Humphrey Davy*, who was Faraday's predecessor at the Royal Institution, succeeded in isolating the two metals for the first time by this means (see page 155).

Faraday's Laws of Electrolysis.—Faraday investigated the relationships between the amount of electricity flowing through a circuit and the quantities of different substances which are liberated by electrolysis. The results of his investigations are summarised in his two laws.

Faraday's First Law of Electrolysis.—The amount of substance deposited or liberated at an electrode is directly proportional to the quantity of electricity passing through the circuit.

The practical unit of quantity is the **coulomb.** It is the quantity of electricity conveyed by a current of one ampere flowing for one second. Hence

$$\begin{array}{c}\text{Quantity of electricity}\\ \text{in coulombs}\end{array} = \begin{array}{c}\text{Current strength}\\ \text{in amperes}\end{array} \times \begin{array}{c}\text{Time in}\\ \text{seconds.}\end{array}$$

It is evident from the first law that the weight of hydrogen liberated by a current of 1 ampere flowing through acidulated water for 3 minutes is the same as the weight liberated by a current of 2 amperes flowing through it for $1\frac{1}{2}$ minutes.

Faraday's Second Law of Electrolysis.—The masses of different substances deposited or liberated by the same quantity

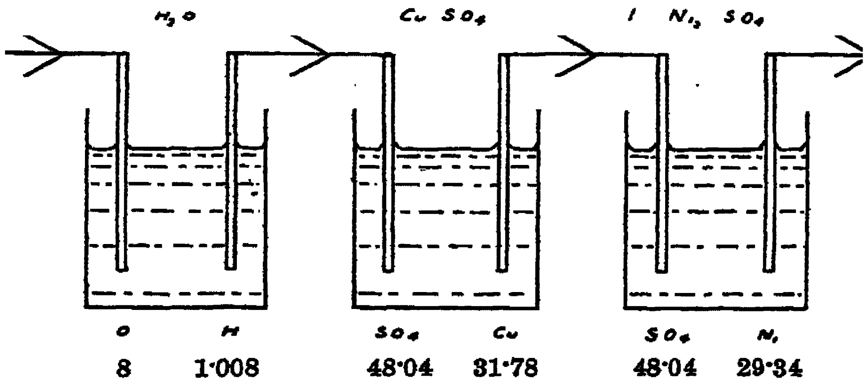


FIG. 112.

of electricity are proportional to the chemical equivalents of the substances.

The **chemical equivalent** *of a substance is the weight of the substance that will combine with or displace unit weight of hydrogen.* It is obtained by dividing the atomic weight of the substance by its valency.

It is clear from the second law that if the same current is passed through acidulated water, copper sulphate solution and nickel sulphate solution (Fig. 112), the weights of the various constituents liberated in a given time are in the ratios given in the figure.

The **electro-chemical equivalent** (e.c.e.) *of a substance is the weight of the substance that is deposited by a current of one ampere flowing for one second through a solution containing the substance in the ionised state.*

Experiment.—To determine the electro-chemical equivalent of copper. This is measured by passing a current between copper electrodes placed in a solution of copper sulphate.

The anode consists of a copper sheet BC (Fig. 113) which is bent twice at right angles, so that it hangs on either side of the copper cathode K. Copper is thus deposited on both sides of the cathode and the maximum area of surface is used. The electrodes are connected as shown (Fig. 114), to a battery B, a rheostat R, an ammeter A, and a key K, care being taken that the anode terminal is connected to the positive end of the battery circuit. The tangent galvanometer T.G. may be omitted. The cathode is thoroughly cleaned with emery paper before it is weighed and inserted in the solution. The magnitude of the current should be regulated by means of the rheostat so that it does not exceed ·02 ampere for each sq. cm. of the surface of the cathode. If the current is greater than this amount, the deposit will not be hard and some of it is liable to be removed when the cathode is washed at the end of

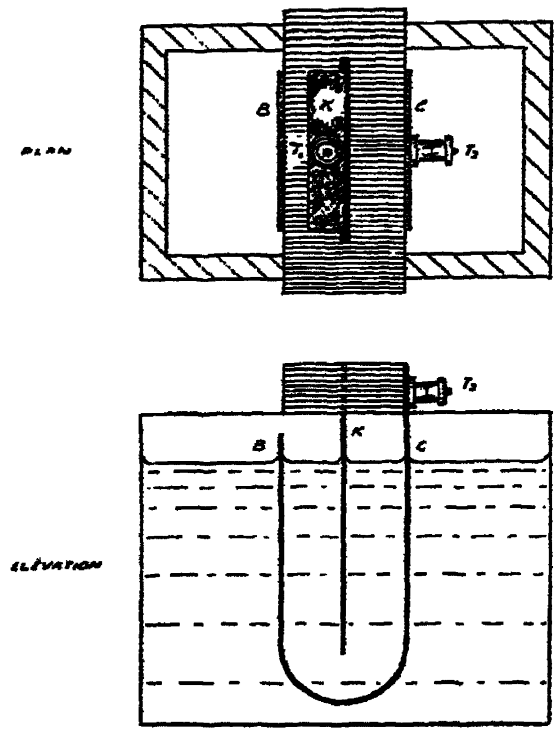


FIG. 113.

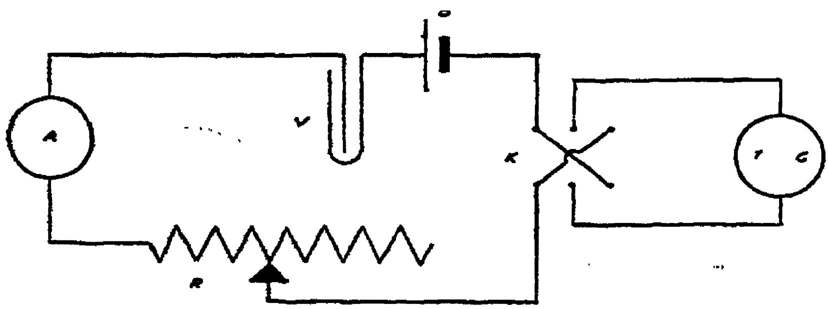


FIG. 114.

the experiment. The washing operation can be performed by holding the plate under a tap. It is then dried by placing it some distance above a low bunsen flame, care being taken that the distance is sufficiently great to prevent oxidation (a spirit flame is preferable for this purpose).

Let W gms. be the increase in the weight of the cathode in t secs. Then if I amperes is the current flowing through the circuit, and z is the electro-chemical equivalent of copper,

$$W = zIt$$

$$\text{or } z = \frac{W}{It}$$

An arrangement consisting of two copper plates immersed in copper sulphate solution is known as a **copper voltameter.** The voltameter can be employed to calibrate an ammeter.

Experiment.—Calibration of an ammeter using a copper voltameter. Connect a battery, a copper voltameter, an ammeter, a rheostat and a key in series. Adjust the rheostat so that the ammeter registers a low reading. Make a note of this reading, and also determine the true value of the current flowing through the circuit from the weight of copper deposited on the cathode in a known time. Repeat, taking a larger value of current, and continue in this manner until the ammeter registers its maximum reading. Tabulate the results obtained in the following manner :

Indicated ammeter reading.	True ammeter reading.	(Indicated—True) reading = Error.

Plot a graph taking the ammeter readings as abscissæ and the errors as ordinates.

Experiment.—To determine the reduction factor (k) *of a tangent galvanometer* (see page 179). Connect up the apparatus as in Fig. 114, taking care to place the ammeter or any inductive resistance at a distance from the tangent galvanometer (Why ?). Clean and weigh the copper cathode and adjust the resistance R to give a current which produces a deflection of approximately 45°. Pass this current for about 40 minutes, reversing the current through the galvanometer every 10 minutes and maintaining its value constant by adjusting the rheostat R if necessary. Read both ends of the pointer. Let θ be the average reading and I (amps.) the current passing

in t seconds. Then $I = k \tan \theta$, and $I = \frac{W}{zt}$ where W is the weight of copper deposited and z is e.c.e. of copper. Hence calculate k.

Electro-chemical equivalents.

Copper, 0·000329.	Oxygen, 0·0000830.
Hydrogen, 0·0000104.	Silver, 0·0011183.
Lead, 0·001072.	Zinc, 0·000337.

THE SILVER VOLTAMETER.—From the table given above, it can be seen that silver has a relatively high electro-chemical equivalent. Consequently it was the substance chosen for the standard measurement of electro-chemical equivalent.

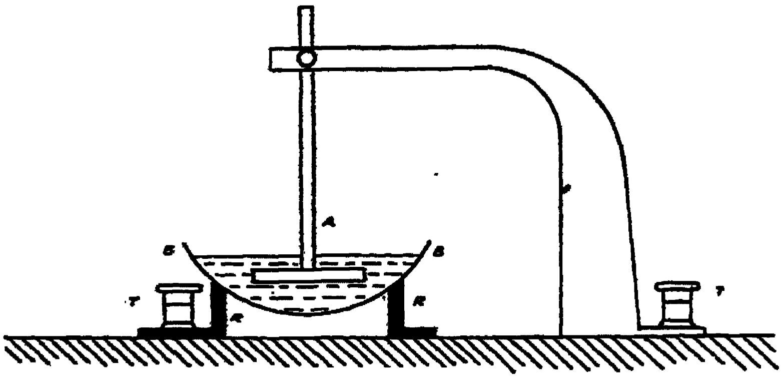


FIG. 115.

The silver voltameter is of the form shown in Fig. 115. The cathode on which the silver is deposited consists of a platinum basin, B, which is supported on a brass ring, R. The basin is first carefully cleaned and weighed and a 15—20% solution of silver nitrate is placed in it. The anode A consists of a plate of pure silver. The current is led in and out by the terminals T,T. When the current passes, silver from the solution is deposited on the cathode, and the (NO_3) ion that is liberated combines with the silver of the anode forming silver nitrate which goes into solution. The strength of the solution is thus maintained. Impurities which may be released from the anode during the process of its disintegration are prevented from passing through to the cathode by a piece of filter paper which is wrapped round the anode. If the weight of silver that is deposited on the cathode in a known time is ascertained and the value of the current is known, the

electro-chemical equivalent of silver can be calculated as in the case of copper. By using the silver voltameter, Lord Rayleigh obtained the value ·0011180 for the e.c.e. of silver.

The ampere, which is the practical unit of current, is defined in terms of the weight of silver deposited by it from a solution. The definition is as follows:

The ampere is that unvarying current which when passed through a solution of silver nitrate in water, deposits silver at the rate of ·001118 gm. per second.

Since the coulomb is the quantity of electricity conveyed by a current of one ampere in one second, it is clear that a coulomb of electricity when passed through a solution of silver nitrate in water deposits ·001118 gms. of silver.

The term **coulometer** (i.e. coulomb-meter) is often used instead of voltameter, and the name indicates that if the e.c.e. of the substance liberated or deposited is known, then the apparatus can be used to measure a quantity of electricity,

i.e. quantity $= i \times t = \dfrac{W}{z}$

Example.—The cathode of a silver voltameter weighs 6·208 gms. before and 6·518 gms. after, a steady current has been passing through the apparatus for 10 minutes. Find the value of the current.

Final weight of cathode = 6·518 gms.
Initial weight of cathode = 6·208 gms.

Difference, i.e. weight of silver deposited (W) = ·31 gms.

Also z (for silver) = ·001118

and t = 600 secs.

Now $W = zIt$

$$\text{or } I = \frac{W}{z \times t} = \frac{\cdot 31}{\cdot 001118 \times 600}$$

$$= 0{\cdot}462 \text{ amps.}$$

Example.—A current passes through a silver voltameter and a copper voltameter which are connected in series. After 10 minutes it is found that 0·30 gm. of copper has been deposited on the copper cathode. What is the weight of the deposit of silver? (At. weight of silver = 108, at. weight of copper = 63·5. Valency of silver = 1, valency of copper = 2.)

$$\text{Chemical equivalent of copper} = \frac{63{\cdot}5}{2} = 31.75$$

$$\text{Chemical equivalent of silver} = \frac{108}{1} = 108$$

By Faraday's Second Law :

$$\begin{array}{ccccccc} \text{Weight of silver deposited} & : & \text{Weight of copper deposited} & = & \text{Chemical equivalent of silver} & : & \text{Chemical equivalent of copper} \end{array}$$

$$\therefore \text{Weight of silver deposited} : 0{\cdot}30 = 108 : 31{\cdot}75$$

$$\therefore \frac{\text{Weight of silver deposited}}{0{\cdot}30} = \frac{108}{31{\cdot}75}.$$

$$\therefore \text{Weight of silver deposited} = \frac{0{\cdot}30 \times 108}{31{\cdot}75} \text{ gms.}$$

$$= 1{\cdot}021 \text{ gms.}$$

Example.—A sheet of metal 10 in. square is to be coated with copper. The sheet is placed in a copper voltameter and a steady current of 2 amperes is passed through the apparatus. How long will it take to complete the operation if the thickness of the coating is to be ·002 in. ? The density of copper is 8·90 gms. per cc.

Volume of copper to be deposited $= 10 \times {\cdot}002$ cu. in.
$= 0{\cdot}02$ cu. in.

Also 1 in. $= 2{\cdot}54$ cms.

$\therefore$ 1 cu. in. $= (2{\cdot}54)^3$ c.c.

$\therefore$ Volume of copper to be deposited $= 0{\cdot}02 \times (2{\cdot}54)^3$ c.c.
$= 0{\cdot}3276$ c.c.

$\therefore$ Weight of copper to be deposited (W) $= 0{\cdot}328 \times 8{\cdot}90$ gms.

Also z (for copper) $= {\cdot}000329$
and I $= 2{\cdot}0$ amperes.

Since $W = zIt$

$$t = \frac{W}{z \times I}$$

$$= \frac{0.328 \times 8.90}{{\cdot}000329 \times 2{\cdot}0}$$

$= 4{,}432$ secs. or 1 hr. 13 mins. 52 secs.

Commercial Applications of Electrolysis.—There are many important commercial applications of electrolysis. One of these is *electro-plating*, a process which consists in the deposition of one metal upon the surface of another. Certain metals such as copper, nickel, zinc, silver and gold are particularly applicable to this process. The objects to be plated are suspended by means of hooks from copper rods (C in Fig. 116), which are in electrical connection with the negative bus-bar. (A bus-bar is a term used in electrical engineering. It refers to a thick copper bar which is carefully insulated and provided with terminals. The supply mains, or poles of the

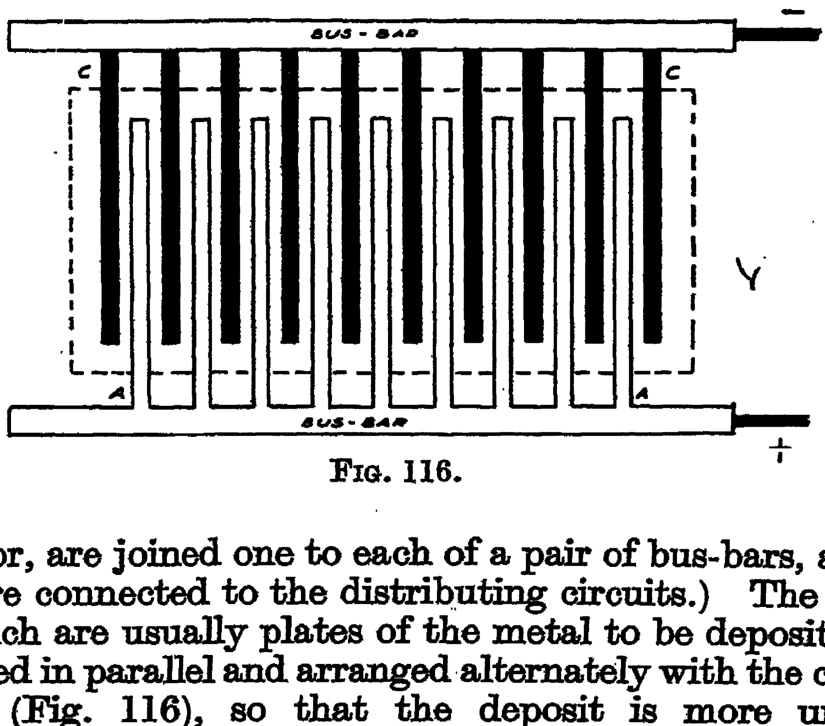


Fig. 116.

generator, are joined one to each of a pair of bus-bars, and the latter are connected to the distributing circuits.) The anodes (A), which are usually plates of the metal to be deposited, are connected in parallel and arranged alternately with the cathode articles (Fig. 116), so that the deposit is more uniform. With the large electrode surface big currents (often of the order of a thousand amperes) may be employed. The current *density* should not exceed about 0·02 amps./sq. cm. to ensure that the deposit is strongly adherent to the plated article. In this latter respect it is also extremely important that the surfaces to be plated are first thoroughly cleaned. This object is achieved by scrubbing the plate with sand, and then washing it in dilute sulphuric acid and finally caustic alkali solution to remove any grease.

Copper has an important rôle in electro-plating. It is very easily deposited electrolytically, and it is found that a copper layer furnishes a very satisfactory surface for the

deposition of other metals on it. For example, difficulty is experienced in depositing silver directly upon iron. If, however, the iron is coated initially with copper, the silver can then be deposited quite easily on the copper coating. Likewise, in gilding iron or tin, the metals are first coated with copper and the gold is then deposited on this coating. Galvanised iron, e.g. roofing, nails, etc., is iron which has been coated with zinc to prevent it from rusting, zinc sulphate being the electrolyte employed.

Copper articles are plated with silver by immersing them in a solution of silver cyanide in potassium cyanide. The anode is a plate of pure silver. Before the invention of this method in 1840, by Wright of Birmingham, copper goods were silver plated by putting a strip of silver on clean copper and then heating and rolling the metals. The product is called Sheffield plate, and the silver coating is thicker than in electro-plated articles. Within recent years chromium plating has become widely used, as it provides a bright surface which does not tarnish. The so-called untarnishable silver articles are formed by electro-plating rhodium or palladium on silver.

ELECTROTYPING is used extensively in the reproduction of statues and other works of art, in printing, in obtaining facsimiles of medals and in similar operations. A cast is first taken of the object which is to be reproduced and this is made in wax, in plaster of Paris, or in gutta-percha (which has been softened by heating). The surfaces of these materials, however, are not conducting and consequently they are rendered so before starting operations, by covering them with powdered graphite. The mould thus obtained is used as a *cathode* in a copper sulphate bath. The anode is of pure copper and when a current is passed a layer of this metal is deposited on the surface of the mould. The current density should not exceed 0·03 amps./sq. cm., and the time of passage will govern the thickness of the deposit, which depends upon the purpose for which the plate is required. The electrotype is then removed from the wax and the shell is backed with an alloy of low melting point, such as type metal, to give it rigidity. The plate, which is a perfect copy of the original, can now be used for printing. A similar process is used to obtain an electrical conducting surface on ebonite or similar material, when the surface is then said to be "metallised."

In the manufacture of gramophone records the original

record is cut by a needle in a wax disc, and this is placed in an electro-plating bath and coated with copper. This copper negative is then electro-plated with silver, which is stripped off to form a hard facsimile of the wax disc. The silver cast is in turn plated with nickel, and this nickel coating when stripped off is the final negative from which the actual records are stamped.

A recent application of electrotyping is in the manufacture of seamless copper (also iron) tubes. For this purpose the cathode negative cast is a revolving drum or cylinder coated with a thin film of oil or graphite, and this is continuously burnished by means of agate brushes. Copper anodes and a copper sulphate bath are used, and it is found that it is possible to employ current densities as high as 0·25 amps./sq. cm.

Electro-Metallurgy.—The applications of electrolysis in metallurgy are very numerous. It forms part of many processes for obtaining metals from their ores, and it is also extensively used in methods for purifying metals. Only a very brief outline of some of these applications can be given here.

A metal that is now widely used for a variety of purposes is aluminium. The principal source from which it is obtained is bauxite, and it is separated from this by an electrolytic process. When iron is removed from this ore, an oxide of aluminium, known as alumina (Al_2O_3) is left. The alumina is mixed with cryolite (a double fluoride of sodium and aluminium) and fluor-spar (calcium fluoride) and the mixture is fused in an iron box, which is lined with blocks of carbon. This fused mixture, maintained at about 900° C. constitutes the electrolyte and, when a current is passed through it, the alumina alone is decomposed. In the Hall process (Fig. 117) the current enters through a carbon anode and leaves through the carbon lining which acts as the cathode. The molten aluminium, which is denser than the electrolyte, collects in a pool on the cathode and the liberated oxygen travels to the rods of carbon acting as the anode, and oxidises them so that they are gradually burnt away. Provision is made for their replacement as they are used up. Copper is used in all kinds of electrical work and it is very important that it should be pure, as the presence of a little impurity considerably increases its resistance. The metal that is derived from ore by the usual metallurgical processes is not pure enough for electrical

purposes. In the process of purification by electrolysis the impure copper is used as the anode and is placed in a tank containing copper sulphate solution to which sulphuric acid has been added. The cathode consists of a thin sheet of copper. When a current is passed through the solution, copper which is very nearly pure is deposited on the cathode, while most of the impurities are dissolved. If silver and gold are present they do not go into solution, but are deposited on the bottom of the tank. Thus, the process not only provides nearly pure copper, but it furnishes a means of

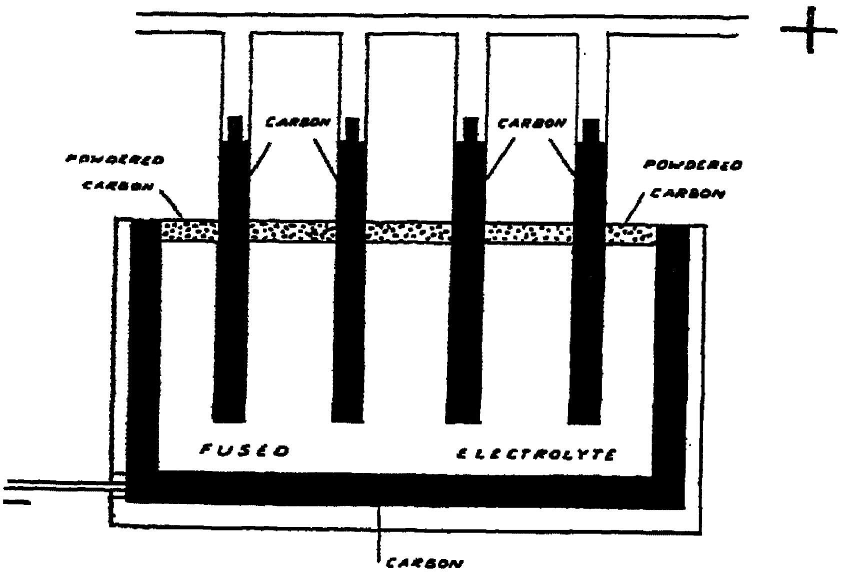


FIG. 117.

recovering the silver and gold which are present. Electrolytic refining is more expensive than furnace refining, but yields a purer product and often enables valuable by-products to be recovered as just indicated. The principal metals which are refined electrolytically are gold, lead, nickel, copper, silver, iron, tin, cadmium and bismuth.

The recent increase in the commercial demands for pure hydrogen, e.g. in the hydrogenation of oils, has given an impetus to the electrolytic production of gases. The utilisation of electrolysis for the manufacture of *oxygen* was previously limited by the inability to dispose of the hydrogen which was simultaneously generated, as otherwise this process would prove uneconomical when compared with other methods of production. In the manufacture of synthetic ammonia and

in various catalytic actions the hydrogen must be very pure and this requirement is effectively satisfied by electrolytic hydrogen which can be obtained from efficient plants at an average purity of not less than 99.9%. Caustic soda (or sometimes caustic potash) is nowadays employed as the electrolyte in preference to sulphuric acid which is liable to create corrosion trouble, and any possible admixing of gases due to the close proximity of the electrodes is prevented by the interposition of a diaphragm.

It is interesting to note that the so-called "*heavy water*" which contains the heavy * *isotope* of hydrogen of mass *two*, is concentrated in the residual liquor obtained by the continued electrolysis of alkaline solutions.

Ionic Medication is an interesting application of electrolysis to medicine, and is the means of introducing substances such as iodine, magnesium, etc., into the human body. A small portion of the skin is covered with a compound containing the desired substance, and a damp pad is interposed between the patch and a platinum electrode. A similar pad and electrode are placed on another part of the body and this electrode is made the cathode or anode according as a +ve ion (such as magnesium) or a −ve ion (as iodine) is to be respectively introduced into the system.

Corrosion due to Electrolysis.—On D.C. (direct current) tramways, except in the case of the conduit system, the track rails are used as the return circuit for the current supplied to the motors, the latter being in electrical connection with the frame and wheels of the car. In other words the rails constitute an "earthed return," which however must not be confused with an "earth return," where the earth itself completes an electric circuit, a device which is often utilised in telephonic and telegraphic work. Unfortunately, despite the careful welding together of the lengths of tram rails in order to form a continuous conductor, a small part of the return current, known as the stray current, flows through parallel conducting paths in the earth or through adjacent gas and water pipes, etc. (see Fig. 118). It is further evident that the electrical conductivity of the soil itself is dependent on its dampness and the quantity of salts left in solution. Corrosion due to electrolysis will consequently take place wherever

* Isotopes are substances which are chemically identical but possess different atomic weights.

the stray current *leaves* the metal (rail or pipe), since this will correspond to the anode of an electrolytic cell and hence will tend to be dissolved. Furthermore, it should also be noted that corrosion will occur on the left hand side of each pipe joint, as owing to the higher resistance of the junction as compared with the rest of the pipe, some current will by-pass the junction through the earth. The amount of corrosion will increase with the density of the current leaving the pipe, and is obviously greatest near to the power station, G. The student should satisfy himself carefully that the corrosion of the pipe would be more *widespread*, if the negative pole of the

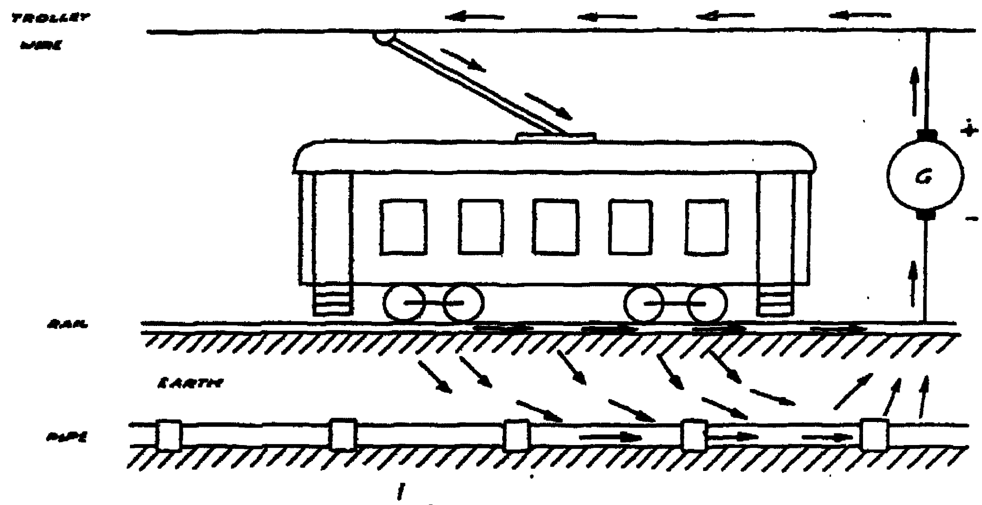


FIG. 118.

generator was connected to the trolley wire. It is interesting to note that lead covered cables are more quickly destroyed than iron pipes, as the e.c.e. of lead is much greater than that of iron.

QUESTIONS.

1. Describe in detail a simple experiment which illustrates the principles of electrolysis and include in your answer the meaning of the terms electrolyte, electrode, anode, cathode. State a practical application of electrolysis. (C. & G., 1929.)

2. State and explain Faraday's Laws of Electrolysis.

Describe an experiment to determine the electro-chemical equivalent of copper.

3. Describe how an ammeter can be calibrated by means of a copper voltameter.

4. Explain the terms: electro-chemical equivalent, cathode and ion. What current must be sent through copper sulphate solution to deposit copper over an area of plate 10 cm. by 1.75 cm. to a thickness of 0.01 mm.

in one hour? Electro-chemical equivalent of copper = 0.000329 gm. per coulomb. Density of copper 8.9 gm./cc. (U.E.I., S2, 1935.)

5. A current is led in and out of a vessel containing water and sulphuric acid by means of platinum electrodes. Describe what takes place in the solution and at the electrodes and state the exact purpose of the acid. Will the solution get weaker or stronger as the experiment proceeds? Give reasons for your answer. (U.E.I., S1, 1933.)

6. Write a short account of some commercial applications of electrolysis.

7. Define the ampere and the coulomb.

How many coulombs will be required to liberate, electrolytically 1 gm. of each of the following substances: silver, copper and hydrogen?

(e.c.e. of silver = 0.001118; e.c.e. of copper = 0.000328, and e.c.e. of hydrogen = 0.0000104.)

CHAPTER IX

CELLS

The Simple Voltaic Cell.—A rod of pure zinc and a plate of copper are placed in a vessel containing dilute sulphuric acid (Fig. 119). If a moving coil voltmeter V is now connected between the metals it will indicate a reading of about 1.08 volts, and furthermore from the manner of connection to the instrument it is easily deduced that the copper plate is at the higher potential. An identical result is observed if a voltmeter is connected across the *terminals* (or plates) of the *cell* shown in Fig. 123.

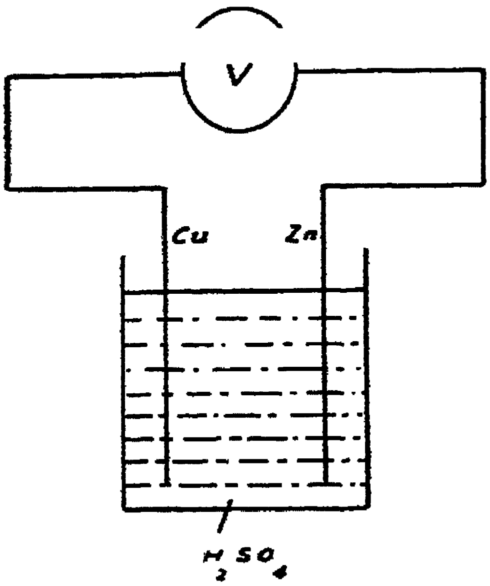


Fig. 119.

An Italian professor of anatomy, Galvani, was the original observer of a similar effect to that described above. He found that if a composite rod, one-half length of iron and the other of copper, was placed so that one end was in contact with the crural nerve of a frog's leg and the other with the muscle of the foot, then distinct muscular contractions could be observed. A few years later, in 1800, another Italian scientist, Volta, constructed his well-known *voltaic* pile (Fig. 120), consisting of a number of pairs of plates of copper and zinc, each dissimilar metal being in contact, and each pair of plates separated from its neighbours by pieces of blotting paper or felt moistened in brine.

In explanation of the above results it must be remembered (Chap. II) that when two metals are brought into contact it is only the electrons which are capable of diffusing across the interface, as the +ve ions are firmly imbedded in the metals

themselves. On the other hand when a metal is placed in a solution of one of its salts, then it is possible for +ve metallic ions to pass across the solid-liquid interface. In the case of a strongly electro +ve metal (i.e. one in which the affinity between the metallic ions and electrons is small) such as Zinc (Zn.), *more Zn ions pass into the solution from the metal than from the solution to the metal.* Hence the solution near the metal will acquire a +ve charge at the expense of the latter, i.e. *the metal will acquire a —ve potential with respect to the solution* (Fig. 121). This potential will quickly attain a certain steady value, such that it will prevent any further unequal movement of the ions in the two directions across the solid-liquid boundary. In the case of a less electro +ve metal such as copper, the *metal attains a +ve potential* with respect to a solution of its salts (Fig. 121).

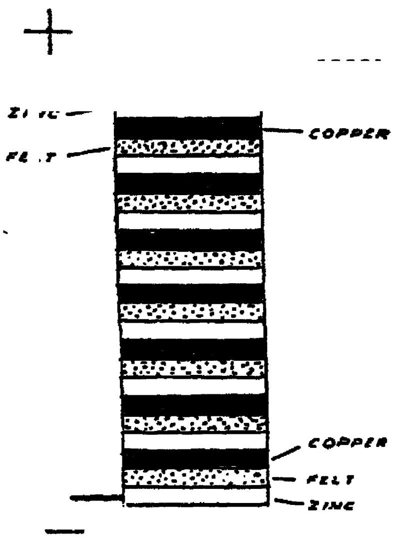


FIG. 120.

It is not necessary, however, that the electrolyte should be a solution of a salt of the immersed electrode, for example a

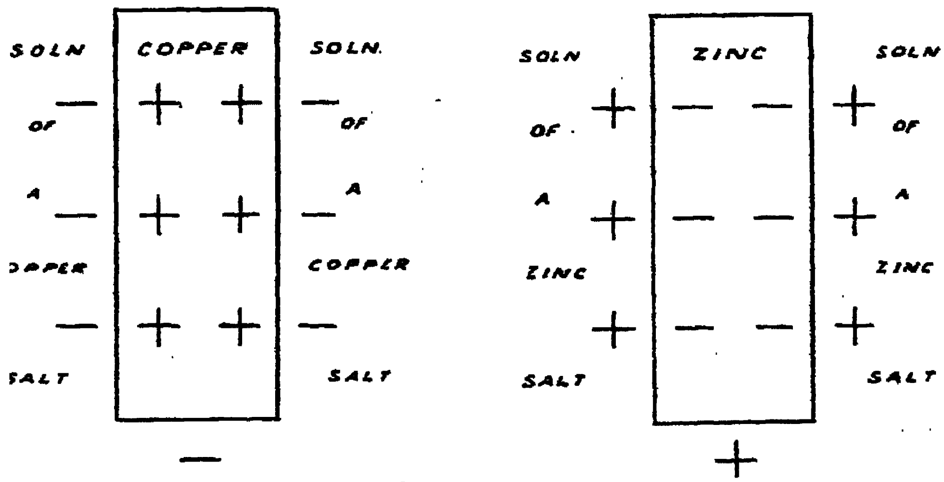


FIG. 121.

copper electrode in a dilute solution of H_2SO_4 attains a +ve potential of 0.46 volts with respect to the solution, while the potential acquired by a zinc electrode is —0.62 volts with

respect to the same solution. Consequently if a copper and a zinc plate are placed apart in a dilute solution of H_2SO_4, the difference of potential between them, as shown by a voltmeter, will be $0.46-(-0.62)=1.08$ volts.

Hence if this arrangement, henceforward referred to as a cell, is connected up in an electrical circuit as shown in Fig. 122, then when the circuit is closed a current is obtained due to this potential difference, and the current can be detected by means of the ammeter A.

The passage of the current will tend to diminish the potential difference between the electrodes, but this will be maintained by further Zn ions passing into solution and more H ions passing from the solution to the copper electrode. The chemical equation representing the internal action of the cell may be written as $Zn+H_2SO_4=ZnSO_4+H_2$.

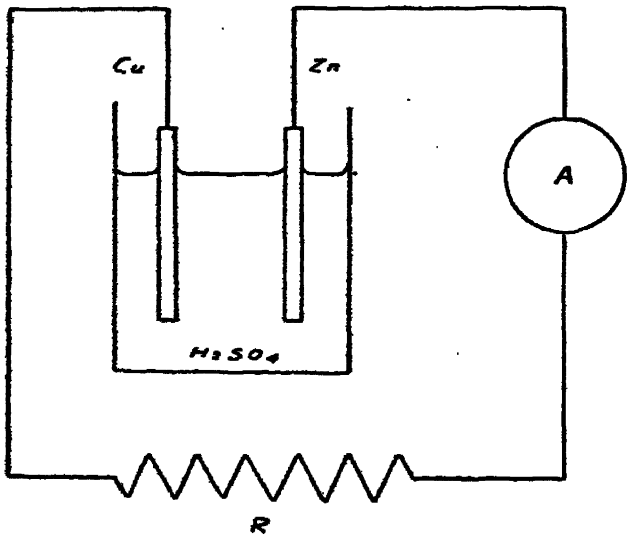


FIG. 122.

The hydrogen is released on the copper plate and gives rise to the phenomenon of **polarisation** which will be dealt with below.

The simple cell described above is an example of a **primary cell**, i.e. one in which a current is produced from the chemical action between the materials of the cell without the aid of any external agency.

The direction of the current flow in the external circuit is from the copper to the zinc, which verifies the fact mentioned above that the copper is at a higher potential than the zinc. It follows that inside the cell the current flow must be from the zinc to the copper.

The potential difference between the two electrodes of a cell when the external circuit is not closed (in this case = 1.08 volts) is known as the electro-motive force (e.m.f.) of the cell. This expression is used to distinguish this P.D. from that in the corresponding electrostatic case. When two charged insulated bodies are joined together a current passes, but

only momentarily, whereas in the case of the cell the current is maintained by the expenditure of chemical energy involved in the consumption of the zinc by the acid.

LOCAL ACTION.—One of the difficulties occurring with a simple voltaic cell is the fact that dilute sulphuric acid attacks commercial zinc, even before the metal is connected to the copper plate. If, however, pure zinc is put in dilute acid, no action occurs. In commercial zinc there are certain impurities present such as carbon and arsenic. Local currents are set up between these and the zinc itself, and the consumption of the zinc that results from this is obviously wasteful. The phenomenon is known as **local action,** and it can be eliminated by amalgamating the zinc. The process consists in rubbing the metal with a mixture of mercury and dilute sulphuric acid. The zinc dissolves in the mercury while the impurities do not. Consequently, when the process is complete, the surface of the plate consists only of amalgam and this alone is in contact with the acid.

POLARISATION.—A simple voltaic cell is said to be polarised when a film of hydrogen gas has collected on its positive plate. As will be explained later a **back electromotive force** is set up in the cell, in consequence of the coating of the copper plate by the gas. Thus, if

E=e.m.f. of the cell on open circuit
and e=back e.m.f. due to polarisation,
then the effective e.m.f. of the cell$=E-e$.

Furthermore, the film of hydrogen offers greater resistance to the passage of the current than does the layer of liquid which it has displaced. Hence, if

R=resistance of the circuit before polarisation occurs
and r=additional resistance due to the film,
then the new circuit resistance$=R+r$.

Let I be the current through the circuit. On applying Ohm's Law to the polarising cell and circuit it follows that

$$I = \frac{E-e}{R+r}$$

It should be quite evident from an inspection of this expression how the two effects of polarisation both tend to reduce the current flowing in the circuit.

Experiment.—The following experiment will illustrate the above facts. Connect a simple cell in series with a fixed resistance (40-50 ω.), a milliammeter and a switch. A short range voltmeter is connected across the cell. On closing the switch observe both voltmeter and ammeter readings every 10-15 seconds, and plot curves showing respectively the current and voltage variation with time. From the latter curve it will be plainly indicated that the e.m.f. of the simple cell becomes smaller when it is delivering a current, and furthermore it should be possible to show that the resistance of the circuit has increased with time, by finding the ratio of the voltmeter to ammeter readings at a few chosen times.

It should be observed that a momentary rise in the current and voltage will be obtained on mechanically rubbing the copper plate with a small brush.

To understand how this back e.m.f. is created it must be remembered that the +ve pole of the cell (the copper plate) corresponds to the cathode (or −ve electrode) of the voltameter. Hence the +ve hydrogen ions (hydrions) travel toward the copper plate during the passage of a current. On reaching the plate these hydrions become neutral molecules of hydrogen gas and these gas bubbles cling to the plate and in time form an insulating layer which will increase the resistance of the cell. Furthermore the +vely charged hydrions approaching the plate will be unable to reach it so that a layer of +vely charged hydrions will be formed, and this layer will tend to repel or drive back other hydrions *towards* the Zn plate. In other words there is a back e.m.f. produced in the cell.

The diminution of current through polarisation is a defect which is inherent in the simple voltaic cell, and the various primary batteries which are in use contain devices which are intended to dispose of it. The mechanical method indicated above is inconvenient in practice, and the methods which are mostly employed involve chemical action.

The Daniell Cell.—This was the first cell devised to give a constant current. Daniell was Professor of Chemistry at King's College, London, and he appears to have had the idea of the cell from some remarks made by Faraday in one of his lectures at the Royal Institution.

The container in a Daniell cell (Fig. 123) is a copper vessel, C, in which is placed some copper sulphate solution, D. A

porous pot P containing dilute sulphuric acid E is placed in this, and the negative pole consists of a zinc rod Z which is immersed in the acid. The acid acts on the zinc and hydrogen gas is evolved. The result of the reaction is represented by the equation

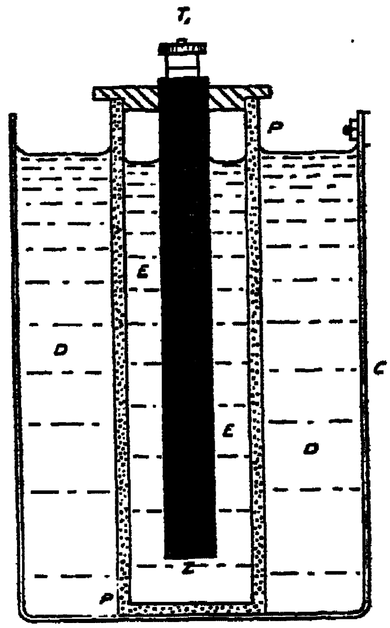


FIG. 123.

$$Zn+H_2SO_4=ZnSO_4+H_2$$

The hydrogen ion escapes through the porous pot into the outer vessel and reacts with the copper sulphate molecules contained in it, with the result that sulphuric acid is formed and copper is liberated.

$$CuSO_4+H_2=H_2SO_4+Cu$$

The copper is deposited on the positive plate and, of course, does not affect the value of the current. The copper sulphate solution is, however, weakened by the process. Consequently the copper container is usually furnished with a perforated shelf on which copper sulphate crystals are placed. These become dissolved and so the solution is maintained at constant strength. The Daniell cell is probably the best known of the two fluid cells. It has an electromotive force of about 1.1 volts.

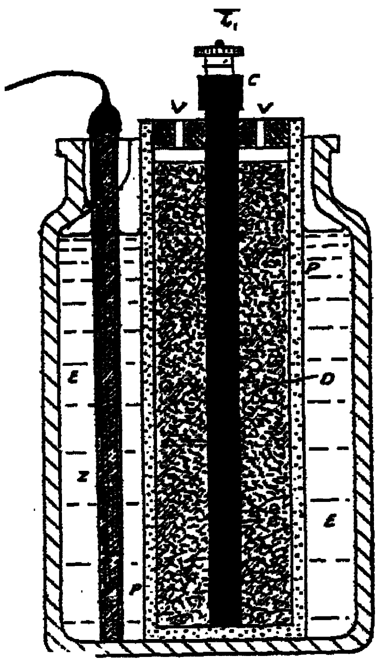


FIG. 124.

The Leclanché Cell.—A common type of single fluid cell is the Leclanché cell, Fig. 124, which was first described by Leclanché in 1868. The positive plate in this case consists of a carbon rod C, which is embedded in a mixture of manganese dioxide and crushed carbon D, contained in a porous pot P. An outer glass vessel contains a solution of ammonium chloride ("sal-ammoniac") E in which is placed a zinc rod Z, which acts as the negative plate. VV are vent-holes.

When the external circuit between the plates is completed and a current is passing, the electrolyte will be decomposed in the manner indicated by the following equation:

$$NH_4Cl \longrightarrow \overset{+}{NH_4} + \overset{-}{Cl}.$$

It must now be noted that the so-called $+ve$ *pole* or plate of a cell corresponds to a *cathode* when the cell is considered as a voltameter, for it is the place where the current passes *out* into the external circuit. Similarly the $-$ve pole corresponds to the anode. It follows that the $-$ve *Cl* ion will travel to the $-$ve pole and on giving up its charge attack the zinc to produce zinc-chloride, viz.: $Zn + Cl_2 \longrightarrow ZnCl_2$.

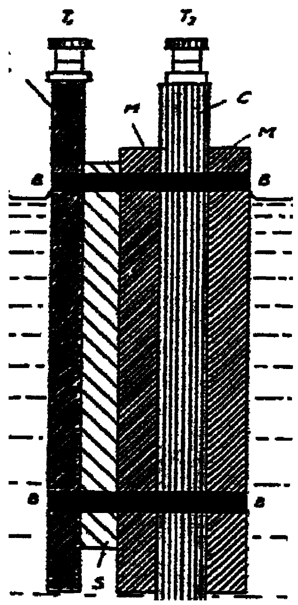


FIG. 125.

The salt formed dissolves in the electrolyte. Likewise the $+NH_4$ ion is discharged at the carbon plate and decomposes into hydrogen and ammonia (NH_3). The latter readily dissolves in the solution, while the hydrogen reduces the manganese dioxide (black oxide of manganese) MnO_2 to Mn_2O_3 (brown oxide of manganese).

The e.m.f. of a Leclanché cell is about 1·43 volts, but, if the cell is allowed to run for an appreciable time it is found that the hydrogen is not oxidised as quickly as it is formed, and consequently the e.m.f. decreases rapidly. It has, however, a fairly quick power of recovery. Owing to this polarisation the Leclanché cell is only used for work where very small or intermittent currents are required, such as in electric bell or telephone circuits. The cell possesses the great advantage that there is only a negligible consumption of zinc when no current is being taken, and hence the only attention which it requires is the occasional renewal of the ammonium chloride solution.

The cell has a high resistance (of the order of 1·0 to 3·0 ω.) which is largely due to the porous pot. This vessel is dispensed with in a later type of Leclanché cell which has been on the market for some years. It is known as the agglomerate cell (Fig. 125). In this cell agglomerate blocks of carbon and manganese dioxide M are held together and are tied against the carbon plate C by indiarubber bands BB. The Leclanché-

Barbier cell (Fig. 125) is constructed on these lines, S being an insulating block and Z the zinc plate. The top of this cell is also closed so as to prevent evaporation of the liquid.

In another type of cell due to Siemens the porous pot is replaced by a sack of textile fabric which only offers a negligible resistance so that the total internal resistance is as low as 0·15 ohm. A recent single fluid cell which has proved very successful is the Codd cell (Fig. 126). There is no porous pot or sack in this cell, which consists of carbon plates C hanging from the lid of a glass jar. An insulated wire also passes through the lid to make connection with a flat zinc plate Z at the bottom of the jar. The depolariser E in this cell being liquid is more rapid in its action than the solid depolariser of the sal-ammoniac cells, and hence gives a higher and more constant voltage. The e.m.f. of the Codd cell is approximately 1·52 volts, and the cell can be used until its P.D. falls to about 1·0 volts.

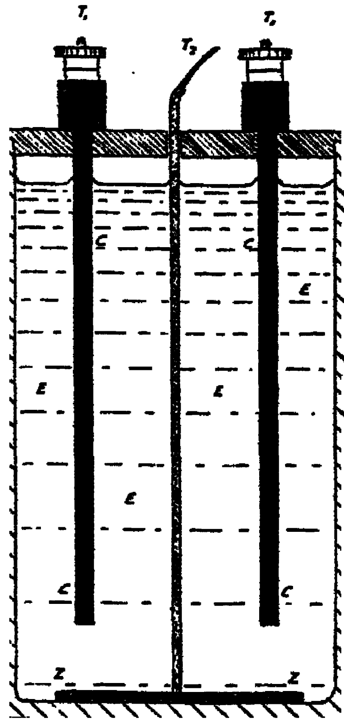


Fig. 126.

The Dry Cell.—This is essentially a type of Leclanché cell, but the substances are present in the form of paste. The cell is thus more portable and more convenient for a variety of purposes than is the liquid cell.

The proportions in which the different substances are present vary with different makes of cell and are trade secrets. The containing cylinder Z (Fig. 127) is usually of zinc. Inside Z, there is a mixture E of zinc chloride, sal-ammoniac, etc. Next comes the mixture of manganese dioxide and

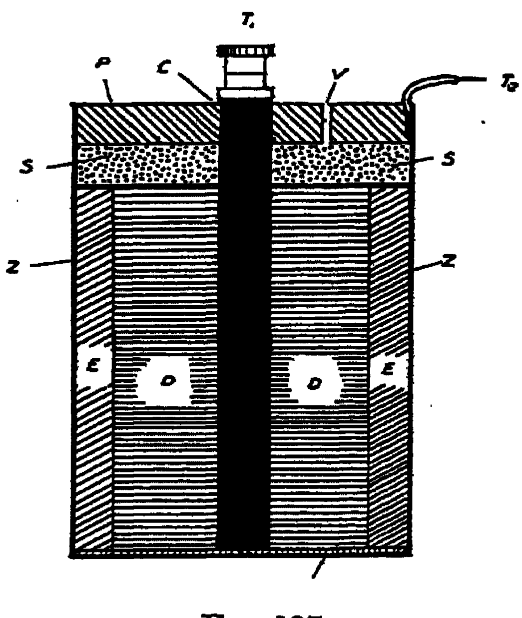


Fig. 127.

powdered carbon D, while a thick carbon rod C passes down the centre. The whole is contained in a case which is sealed with pitch P, and which is provided with a vent V for the escape of gases. S denotes a layer of sand or sawdust.

The electro-motive force of a dry cell is usually about the same as that of a Leclanché cell. Its resistance, however, is considerably lower, being only about one-quarter of that of the Leclanché cell.

The term "dry cell" is rather misleading because moisture is essential for the generation of an electric current by chemical means. It is true that dry cells which are prepared for export to tropical countries have their exciting agent in an absolutely dry and inactive condition. A corked tube is, however, fitted into these, and when the cell is required for use water is poured into this tube and is gradually absorbed by the exciting agent. Dry cells are employed extensively in high tension batteries, which are used for providing the high voltages (100-200) required to be applied to valves in wireless receiving circuits. The cells, connected in series, are suitably encased in a pitch compound and "tappings" for every 12 volts are usually provided. A typical 120 volt battery has a capacity (page 171) of 144,000 milli-watt hours.

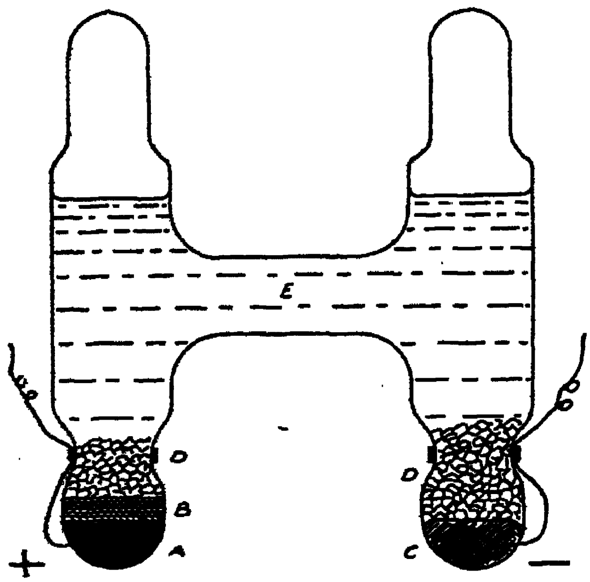


FIG. 128.

The Standard Cell.—This type of cell is useful because its electro-motive force is accurately known and remains constant at a given temperature. The cell is used as a standard of electro-motive force, and not for the purpose of furnishing a current.

The *Weston Cadmium Cell* is a widely used type of standard cell. In its modern form, it is an H-shaped vessel (Fig. 128), consisting of two tubes which are closed at one end and connected by a cross tube. The positive electrode of the cell consists of mercury A, which is placed at the bottom of one of

the tubes. Cadmium amalgam C, or sometimes a rod of cadmium, is placed at the bottom of the other tube and forms the negative electrode. The positive electrode is covered with a paste (B), which is formed by mixing mercurous sulphate with cadmium sulphate crystals and a saturated solution of cadmium sulphate. Crystals of cadmium sulphate, D, are placed in contact with the negative electrode and a convenient quantity of saturated cadmium sulphate solution E is then added to both limbs. Platinum wires are sealed through the bottom of each tube and these serve as terminals for the cell.

The Weston cadmium cell has an electro-motive force of 1·0183 volts at 20° C. The variation of this electro-motive force with temperature is very small.

Back Electro-motive Force in a Voltameter.—When the constituents of a solution are separated by electrolysis, they tend to recombine again by virtue of the potential energy which they possess when in the separated state. Thus, in the decomposition of acidulated water, it is found that a certain minimum electro-motive force of about 1·5 volts is required to maintain a current through the electrolyte. This can be demonstrated experimentally by applying an electromotive force lower than 1·5 volts, e.g. that furnished by a single Daniell cell, to a circuit containing a galvanometer and a water voltameter. The current at first generated soon diminishes to a very small value, and the evolution of gases at the electrodes likewise ceases after a very brief time. This drop in the value of the current is due to the back electromotive force developed at the electrodes.

The polarisation due to a layer of gas on the electrodes generally disappears in a comparatively short time, but it is possible to maintain a state of polarisation in some cases for a long period of time. These cases are those in which a definite change takes place in the nature of the electrodes as will be illustrated by the experiment described below.

The Accumulator or Storage Cell.—In 1859, Planté devised a method of storing the energy liberated when a current is passed through dilute sulphuric acid in which lead plates are inserted as the electrodes. The principle of the method can be illustrated as follows :

Experiment.—Two lead plates are immersed in dilute sulphuric acid contained in a voltameter, V (Fig. 129). The terminals of the plates are connected through the key K_1,

to the battery B, and through the key K_2, to the galvanometer G. If the key K_1 is closed, and the key K_2 is kept open, a current flows through the voltameter, and it is found that the cathode gradually becomes covered with a brown layer of lead peroxide. If next, the plug is removed from the key K_1, and inserted in the key K_2, a current flows through the galvanometer, G. This shows that the voltameter has been transformed into a cell. In other words, it has stored some of the energy of the current that passed through it.

The **accumulator is termed a secondary cell** since its action is dependent upon an auxiliary source of current.

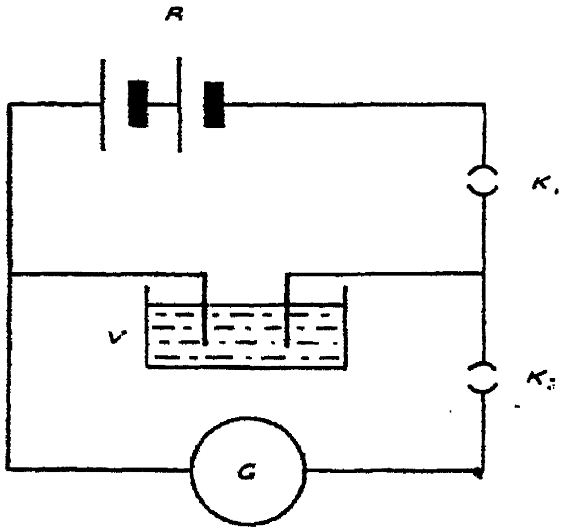


FIG. 129.

The student should observe, however, that the cell does not store electricity. It is chemical energy that is stored, and this can be redeveloped into electrical energy. The accumulator must be distinguished, in this respect, from the condenser (page 52).

A cell that has undergone only one "charging" cannot supply a current for any length of time. Planté's great work was to devise a method for *forming* the plates. This consists essentially of coating the anode with a semi-porous film of lead peroxide. This is done by sending a current through the cell first in one direction and then in the opposite direction. This operation is repeated until the layer of lead peroxide on the anode is sufficiently thick to protect the lead from further action.

The process of "forming" the plates in this manner proved to be so tedious and expensive that, although the cell had a higher electro-motive force than any primary battery, it was not adopted for commercial purposes. In 1881 Faure introduced a new device. He coated the lead plates with a layer of minium or red oxide of lead (Pb_3O_4) which he had made into an adherent paste by mixing with dilute sulphuric acid. Afterwards, he found that litharge or lead oxide (PbO) was more satisfactory for preparing the paste for the

negative plate. The plates are charged and recharged as in the method devised by Planté, but the process is much shorter.

The reaction between the red lead and the dilute sulphuric acid is given by the equation :

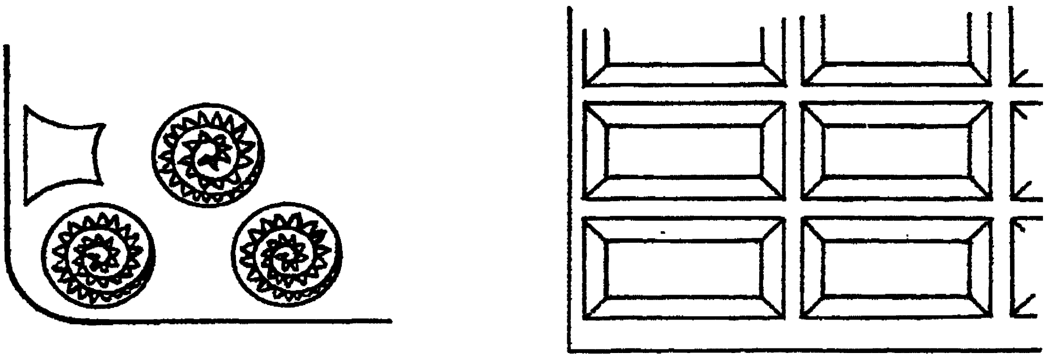
$$Pb_3O_4+2\ H_2SO_4=PbO_2+2\ PbSO_4+2\ H_2O.$$

The lead peroxide and the lead sulphate which are formed settle as a hard porous mass on the plate.

When lead oxide is used in place of red lead the reaction is as follows :

$$PbO+H_2SO_4=PbSO_4+H_2O.$$

The paste plates are much cheaper than the formed plates and are quite satisfactory for use as negatives. It is found,



(*a*) Fig. 130. (*b*)

(*a*) Formed Plate with inset of corrugated lead spirals.
(*b*) Grid of a pasted plate.

however, that in the case of positive plates, the paste is liable to expand and to break away from its supports. On this account Planté plates are frequently used as positives, especially when the accumulators are used for heavy work. Owing to their lightness pasted plates are always used in car batteries.

In practice, it is found advantageous to increase the surface area of the plate that is exposed to the electrolyte. In order to effect this, small pockets can be made in the plates and the active material is forced into these pockets. Corrugated or ribbed plates are also manufactured, and the surface developed in this way is sometimes about ten times larger than the corresponding smooth surface. Figs. 130 (*a*) and (*b*) show respectively a formed and a pasted plate.

The capacity of an accumulator is usually measured in ampere-hours. A 60 ampere-hour cell will give approximately

10 amperes for 6 hours, 5 amperes for 12 hours and so on. An accumulator is also sometimes rated by giving the "normal" current, or the continuous current, that the cell can furnish for a certain number of hours.

The **quantity efficiency** of a lead accumulator is about 90%, as defined by the ratio $\frac{\text{amp.-hours output}}{\text{amp.-hours input}}$. The **energy efficiency,** however, as defined by $\frac{\text{watt-hours output}}{\text{watt-hours input}}$ is only about 75%. This lower value is brought about by the fact that the charging voltage is always appreciably greater than the discharging voltage.

The capacity of an accumulator is increased by connecting in parallel all the positive plates of the cell and also all its negative plates. If the positive plate is placed on the outside it is liable to buckle or warp. This can be prevented by placing a negative plate on the outside at each end of the cell. The number of the negative plates thus exceeds that of the positive plates by one.

The electro-motive force of a fully charged lead accumulator during charging is approximately 2·4 volts, but rapidly falls on discharge to about 2·1 volts. Its internal resistance is low and varies with the size of the cell, being about $\frac{1}{200}$ ohm for a small cell and much less for a large cell. The resistance, however, increases during discharge. This is because water is formed during the process and the density of the acid is consequently diminished. It should be noted that the resistance of any cell will depend upon (1) the concentration of the electrolyte, (2) the area of the electrodes, and (3) the closeness of the electrodes to one another. If B is the cell resistance and I the current flowing at any time, the voltage drop in the cell is IB. It is evident that the smaller this quantity (due to a low value of B), the less will be its effect on the steadiness of the output of the cell, when delivering currents of varying magnitudes. An accumulator should not be worked after its electro-motive force has fallen to 1·8 volts, as the cell then soon becomes ruined through the formation of an insoluble sulphate of lead.

The resistance of dilute sulphuric acid is a minimum when the specific gravity is about 1·22. During discharge the

specific gravity of the acid falls from 1·22 to 1·18, and this criterion is the better method of judging the condition of an accumulator.

Great care should be taken to avoid short circuiting or overloading an accumulator as this results in sulphating, and also owing to its low resistance large currents will be produced, with a consequent disintegration of the plates due to the excessive heating. For example, with a single accumulator of resistance 0·005ω the current produced on short-circuiting would be equal to $\frac{2 \cdot 1}{0 \cdot 005}$ amps., i.e. 420 amps. A momentary short circuit, however, appears to do little harm as car batteries used for "starting," deliver 400-500 amps. for the short period required.

The Edison Accumulator.—The advantage of this alkaline accumulator over the lead acid accumulator consists in the fact that it is more durable and that it can be discharged completely without having any injurious effect upon it. It can also be left for some time in this condition. On this account it is particularly suitable for use in places where careful attention is impracticable. The electrolyte is a 21% solution of potassium hydrate, to which a small quantity of lithium hydrate has been added. The positive electrode consists of nickel hydrate which is contained in a nickel framework, while the negative electrode comprises a nickel plated steel plate. The container of the cell is itself made of nickelled sheet steel, adding thereby to its robustness. The disadvantages of this type of accumulator are its increased cost and the fact that its e.m.f. is much lower, being only about 1.2 volts. The quantity and energy efficiencies of the nickel alkaline accumulator are respectively about 80% and 60%.

Accumulators are used for a large variety of purposes as, for example, in telephone exchanges and broadcasting stations, in wireless receiving sets for heating the filaments of valves and also in the form of high tension "batteries" for supplying the necessary high voltages to the "anodes" of valves and in motor cars for starting and ignition purposes. These secondary cells are also employed in D.C. three-wire power supply systems to ensure continuity of operation by storing energy during the periods of "low-load" (i.e. small demand) so that the normal output can be supplemented during "peak"

periods to meet any increased demand. Other important uses are in the lighting of electric trains, when they are often charged by axle-driven generators, and in electric traction. In the latter case the nickel accumulator gains preference over the lead type on account of its lightness and mechanical strength, and further by the fact that it admits of large currents being taken without damage. In this connection a new design of accumulator called the Drum Cell, consisting of +ve plates containing nickel hydroxide and —ve plates of nickel-gauze grids immersed in a solution of zinc oxide in potash, possesses the desirable quality of allowing itself to be rapidly charged and discharged without injury. The current efficiency of the Drum accumulator is 92.5% and its energy efficiency 75%. Cells used for electric traction will, of course, require to be frequently charged up at convenient stations en route.

Example.—A large battery comprising 40 accumulators is charged at 4·0 amps. for 13 hours, and is discharged at a constant current of 2·5 amps. for 18 hours. Determine the quantity efficiency of the battery.

$$\text{Quantity Efficiency} = \frac{\text{Amp.-hours Output}}{\text{Amp.-hours Input}} \times 100\%$$

$$= \frac{2{\cdot}5 \times 18}{4{\cdot}0 \times 13} \times 100\%$$

$$= \mathbf{86{\cdot}5\%}.$$

If the average P.D. of each cell during charging and discharging is respectively 2·28 volts and 1·94 volts, calculate the energy efficiency of the battery.

$$\text{Energy Efficiency} = \frac{\text{Watt-hours Output}}{\text{Watt-hours Input}} \times 100\%$$

$$= \frac{1.94 \times 2.5 \times 18}{2.28 \times 4.0 \times 13} \times 100\%$$

$$= \mathbf{73.6\%}.$$

Example.—If in the previous problem the battery is to be charged from a 220 volt mains, determine the necessary resistance to be connected in series with the battery, in order to obtain the requisite charging current of 4·0 amps. The internal resistance of each cell is to be taken as 0·01 ohm.

Now the e.m.f. of the battery itself is $40 \times 2{\cdot}28 = 91{\cdot}2$ volts.

But this e.m.f. opposes the applied P.D. so that the effective e.m.f. is $220-91{\cdot}2=128{\cdot}8$ volts.

The current passing $=4{\cdot}0$ amps.

$\therefore$ Total Resistance of circuit must be

$$=\frac{V}{I}=\frac{128{\cdot}8}{4{\cdot}0}=32{\cdot}2 \text{ ohms.}$$

But the internal resistance of the battery $=40\times{\cdot}01=0{\cdot}4$ ohm. Hence the required series resistance $=32{\cdot}2-0{\cdot}4=$ **31·8 ohms.**

The large amount of energy wasted in the series resistance of the charging circuit is avoided by the use of a motor-generator set. In this arrangement a generator is coupled to a motor which is driven from the mains supply, but the P.D. delivered by the generator is adjustable to the requirements in hand.

QUESTIONS.

1. What is understood by "polarisation" and "local action" in primary cells.

Make a sketch showing the internal construction of a dry cell and name the parts. (U.E.I., S1, 1935.)

2. What is meant by the terms "polarisation" and "internal resistance of a cell?" Describe, with a sketch, the construction and action of a simple cell using a depolarising agent. (C. & G., 1935.)

3. When the poles of a Leclanché cell are connected to a galvanometer of negligible resistance, the current, as shown by the deflection of the needle, is observed to diminish rapidly, When, however, a high resistance galvanometer is used, the value of the current, represented by the deflection, remains practically constant. How do you account for this? (C. & G., 1921.)

4. Describe briefly the construction of the lead secondary cell. How can the state of charge of the cell be determined? (N.C.T.E.C., 1934.)

5. Describe the construction of a nickel-iron-alkaline cell.

What are the relative advantages and disadvantages of this type when compared with a lead-acid cell? (U.L.C.I., B, 1935.)

6. What is meant by the "capacity" and the "efficiency" of a secondary battery, and on what do their values depend?

Determine the ampere-hour and the watt-hour efficiency for the following case: Charging current: 10 amps. for 20 hours. Discharge complete to normal limit: 5 amps. for 34 hours. Mean p.d. 2·3 volts during charge, and 1·95 volts during discharge. (N.C.T.E.C., 1934.)

7. Carefully distinguish between and give examples of the following types of cells: Primary, Secondary and Standard.

8. A voltmeter is placed across the terminals of a secondary battery. As the current taken from the battery is increased the reading of the voltmeter falls. Why is this? A secondary battery has an e.m.f. of 110 volts and an internal resistance of 0·25 ohm. A voltmeter connected to the terminals of the battery reads 100 volts when a certain current is taken from the battery. Calculate the value of the current and the resistance in series with the battery. (U.E.I., S1, 1933.)

CHAPTER X

CURRENT MEASURING INSTRUMENTS

GENERAL PRINCIPLES OF A CURRENT-MEASURING INSTRUMENT.—In any such instrument the mechanical force producing a deflection of the pointer (or other indicator) is known as the deflecting force, and may be produced by utilising either the electro-magnetic or the thermal properties of a current. In order that the deflection of the instrument may be proportional to the current flowing an opposite or controlling force must be exerted, and this may be provided in a number of ways. In ammeters and voltmeters the control force is a gravity or spring control, while in galvanometers of the moving-coil type the torsion of a suspension wire (or strip) is employed. On the other hand with moving-needle galvanometers, the earth's magnetic field (or other permanent magnetic field) provides the force which restrains the deflection.

There are essentially two systems in every indicating system, one fixed and the other capable of a relative movement, which should be governed by a simple law with regard to the quantity being measured. In order that the readings should be taken in the minimum time, some form of **damping** device must be incorporated in the instrument. This necessity is due to the fact that in moving to its final deflected position, the pointer of a feebly damped (i.e. *under-damped*) system would initially overshoot this mark (Fig. 131) on account of the momentum of the moving parts. Compare the case of an extended vertical spring which is released. The pointer may swing to an extreme position that is nearly double the true deflection and on swinging back it overshoots its final position in the reverse direction, and these oscillations of the system about the true deflection might continue for an inconveniently long period. Furthermore, using such an instrument it would be impossible to obtain the true reading of a fluctuating current at any particular instant.

If the moving system shows no oscillation about its final deflected position the instrument is said to be *critically damped* or **dead beat** (see Fig. 131). In practice slight under-damping is usually arranged so that the pointer swings only a small amount past its final position before coming to rest, and in this way any " sluggishness " (i.e. mechanical friction) of the instrument can be detected.

The main types of damping employed are air damping, fluid damping and eddy-current damping. The latter type

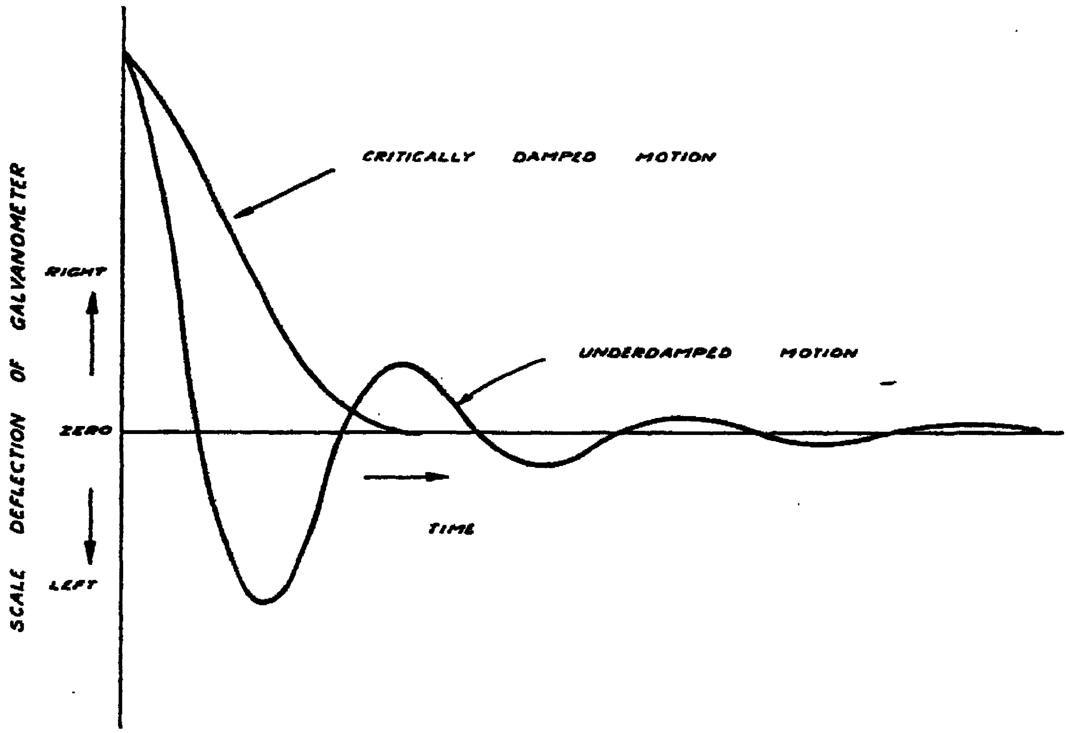


FIG. 131.

of damping depends upon the reaction of the induced eddy currents set up in a moving conductor, with the magnetic field producing them (page 268). In air damping a light vane, moving in a chamber, is attached to the moving system, and the amount of damping is controlled by the adjustment of the clearance space.

GALVANOMETERS are instruments used for the detection or measurement of small currents. The three main classes of galvanometers are, (1) moving-needle, (2) moving-coil, and (3) thermo-instruments. The latter type, however, are primarily used in alternating current measurements and will not be considered here.

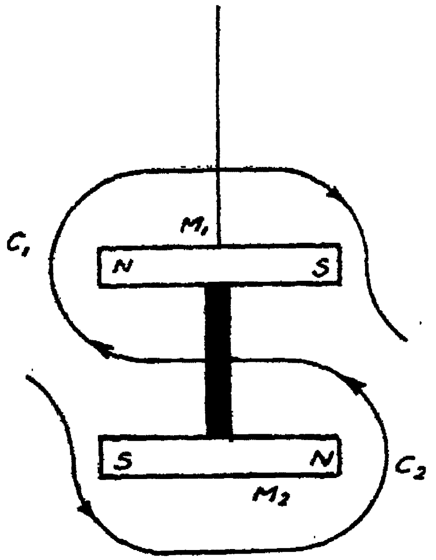


FIG. 132.

(1) Moving-needle Galvanometers. These are a development of Oersted's discovery (1815) that an electric current flowing in a conductor deflected a magnetic needle near it, the magnitude of the deflection being controlled by the earth's magnetic field. In 1820 a German name Schweigger *increased* the *deflecting force* by employing loops of wire (page 79), and in 1825 an Italian, Nobili, further endeavoured to increase the sensitivity of the instrument by *decreasing* the *controlling force*. The latter effect is obtained by the *astatic* arrangement indicated in Fig. 132, where M_1 and M_2 are two similar magnets of nearly equal moments. The magnets are parallel to each other with their similar poles in opposition, and they are *rigidly* connected together by a *short* rod. It should be verified carefully that the deflecting force on each magnet due to the current flowing in the corresponding coils C_1 and C_2, will be in the same direction, but that the direction of the controlling force of the earth's field on M_1 will be in the opposite sense to that on M_2, i.e. the *controlling force is proportional to the difference of the magnetic moments* of M_1 and M_2.

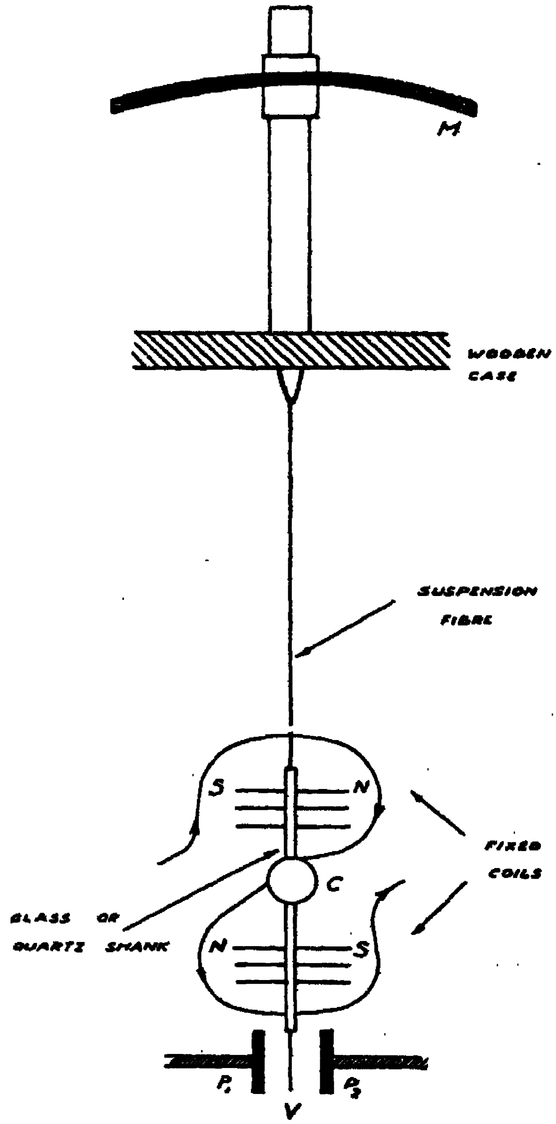


FIG. 133.

In 1858 Sir Wm. Thomson afterwards **Lord Kelvin**, increased the sensitivity of the needle-galvanometer by a device now employed on all instruments for sensitive work, viz. the use of a concave mirror, C (Fig. 133) fixed at the lower end of the suspension. A beam of light is focussed on the mirror and is reflected back on to a horizontal graduated scale, where, with proper adjustment it appears as a well defined spot. Any rotation of the mirror will cause the spot of light to travel along the scale, which is generally about 1 metre distant from the mirror. By this means the *deflection is magnified considerably*, and the arrangement is equivalent to a long pointer attached to the suspended system, without, however, the disadvantages of an increase of mass.

The position of the auxiliary magnet M (Fig. 133) may be varied to make the *control field* less or greater than that due to the earth, and in this way the sensitivity of the galvanometer is correspondingly increased or decreased. In the modern development of the Kelvin needle type such as the Paschen instrument (which can measure currents as small as 10^{-11} *amp.*), it becomes vitally necessary to shield the galvanometer from external fields and soft iron cylindrical shields are utilised. V (Fig. 133) is a light vane moving between fixed plates P_1 and P_2 so that the motion of the suspended system is damped.

The Tangent Galvanometer.—This simple laboratory instrument was devised by Pouillet in 1840, and consists essentially of a *small* bar magnet suspended or pivoted at the centre of a large vertical circular coil (say 15 cms. diam.). A light aluminium pointer (7–10 cms. long) is fixed at right angles to the magnetic needle, and it moves over a circular scale marked in degrees.

Since the magnetic field at the centre of the circular coil produced by the passage of a current is perpendicular to the plane of the coil, it is obvious that the horizontal axis of the coil must not coincide with the magnetic meridian, if the needle is to be deflected. The plane of the coil is usually set in the magnetic meridian and the theory of the instrument for this arrangement is developed below. Fig. 134 shows a section of the galvanometer coil AB in a horizontal plane containing the suspended needle, which is supposed to be situated at O.

Let F=strength of magnetic field (in gauss) at O, produced by a current of i amps. in the coil,
n=number of turns in the coil,
r=radius of the coil (in cms.),
and H=strength of horizontal component (in gauss) of the earth's magnetic field.

The size of the magnet is assumed to be sufficiently small that the value of F can be considered constant throughout its volume. Let θ be the angle of deflection produced by F, then the deflecting couple is given by $2 \times m\mathrm{F} \times \mathrm{OP}$ and the restoring couple by $2 \times m\mathrm{H} \times \mathrm{OQ}$, where m is the pole strength of the suspended magnet.

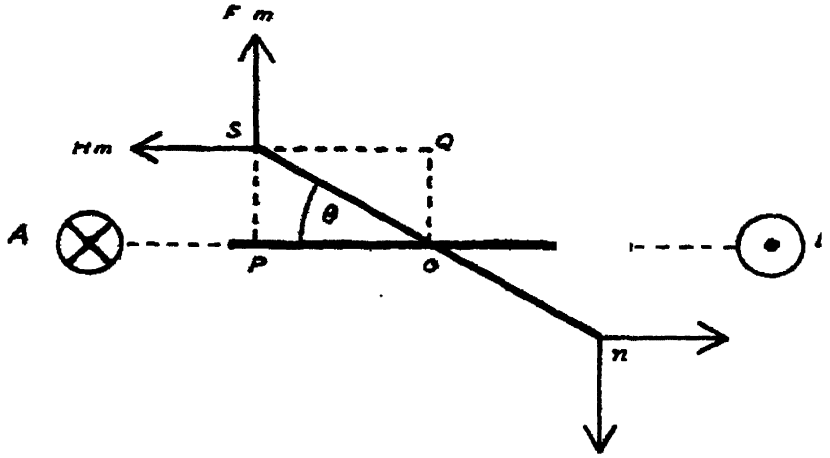


FIG. 134.

For equilibrium $2m\mathrm{F} \times \mathrm{OP} = 2m\mathrm{H} \times \mathrm{OQ}$.

$$\text{Hence } \mathbf{F} = \mathrm{H}.\ \frac{\mathrm{OQ}}{\mathrm{OP}}$$

$$= \mathrm{H}.\ \frac{\mathrm{SP}}{\mathrm{PO}}$$

$$\text{or } \mathbf{F} = \mathbf{H} \tan \theta.$$

Now $\mathrm{F} = 2\pi n i/10r$. Hence $i = \frac{10r}{2\pi n} . \mathrm{H} \tan \theta$ (in amperes)

i.e. $i \propto \tan 0$ or $\mathbf{i} = \mathbf{H/G} \tan \theta$,

where $\mathrm{G} = \frac{2\pi n}{10r}$ is known as the galvanometer constant.

It is a characteristic of a particular instrument and is independent of the value of H, which in general varies from place

to place. If, however, the galvanometer is kept fixed in position the law of the instrument may be written as $i=k \tan \theta$, where k is a constant so long as H at that particular place does not vary appreciably. k is known as the *Reduction Factor* of the galvanometer.

The following experiment is to verify the tangent law of the galvanometer :

Experiment.—Connect the apparatus as in Fig. 135, taking care to widely separate the tangent galvanometer T.G. and the ammeter A, as the latter contains a powerful magnet. Adjust the plane of the coil to be in the magnetic meridian, and vary the resistance R until a deflection of say 20° is

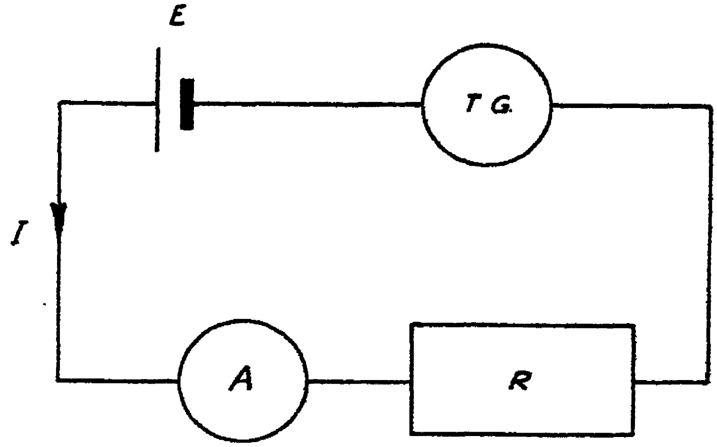


FIG. 135.

produced by the current passing in the circuit. Record the ammeter and galvanometer readings, taking care to observe both ends of the pointer. Diminish the resistance slightly and again obtain a pair of readings ; continue in this manner until a deflection of about 75° is obtained. Tabulate as below ; readings should also be taken with the current reversed.

Ammeter Reading i amps.	Galvanometer Deflection (θ) degrees.			$\tan \theta$	$k=\dfrac{i}{\tan \theta}$
	(1)	(2)	Mean		

Alternatively plot $\tan \theta$ against i, and the slope of the resulting straight line enables k to be evaluated. It is evident that when k is known the instrument can be employed to measure current.

Exercises.—(1) Determine the number of turns of wire in the coil of the given tangent galvanometer, the value of H being known. It follows from the law of the instrument that $n = \frac{10r\text{H}}{2\pi i} \tan \theta$, and the procedure is the same as in the previous experiment, the value of r being measured as accurately as possible.

(2) Determine the value of H in the laboratory knowing the constants of the given tangent galvanometer.

(2) **Moving-Coil Galvanometers.**—This type of instrument owes its inception to Faraday's discovery, in 1821, that a current carrying conductor, if free to move, would continuously rotate around a magnet pole. The first galvanometer embodying this principle was devised by an Englishman named Sturgeon, in 1836, and he employed a coil of copper wire suspended by a metal wire in the field of a permanent magnet. The current was led into the coil by the suspension, and out by a flexible spring attached to the lower extremity of the coil. The sensitivity of this arrangement is greatly increased by the insertion of a cylindrical iron core inside, but perfectly free from the coil. In this way the lines of force are concentrated, with a consequent increase of the deflecting couple (page 77) for a given current in the coil. An instrument employing this idea was designed by Sir Wm. Thomson in 1867, in connection with the trans-Atlantic cable. It was called a *siphon-recorder*, and consisted essentially of a moving-coil galvanometer, incorporating an inking arrangement so that the extremely feeble signals transmitted by a long submarine cable could be both detected and recorded.

In 1882 *D'Arsonval* introduced curved magnet poles, and his modification of the moving-coil galvanometer is typical of the laboratory form of this instrument which is in general use to-day.

The suspended coil C is situated in the narrow gap between the poles of a permanent cylindrical (as in Fig. 136) or horseshoe magnet, and it is usually wound with well-insulated copper wire. In order to preserve the lightness of the coil a smaller number of turns is likely to be used than in the

moving-needle instrument, which consequently in general has a greater resistance. The suspension S which carries both the coil and the concave mirror, M, is soldered to an adjusting screw, A, at its upper end, and is usually a phosphor bronze strip. A thin strip is used in preference to a wire of the same mechanical supporting strength, as it provides a smaller torsional control and this leads to an increased sensitivity. The current is led away from the coil by a loosely-coiled spiral L, which does not exert any appreciable control on the movement of the suspended system.

By the use of the curved magnet poles and the soft iron core, I, a radial magnetic field is produced in the pole-gap as indicated by the dotted lines in Fig. 136. As a consequence for quite large deflections the plane of the coil is always parallel to the lines of force, and hence the deflecting couple is *constant* and given by $iHAn$ (page 77), where n is the number of turns in the coil. If the current i produces a deflection θ of the coil from its zero position, then in this deflected position the torsional couple exerted by the suspension will be $\tau\theta$, where τ (tor.) is the torsional couple for unit angular twist of the wire.

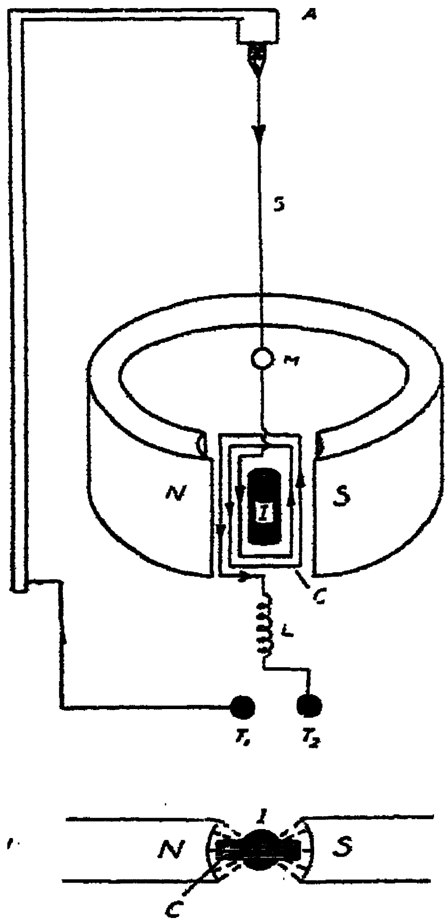


FIG. 136.

Hence it follows (page 77) that $iHAn = \tau\theta$ or $i = \frac{\tau\theta}{HAn} = K\theta$, where K will be a constant for the instrument.

If the coil of a moving-coil galvanometer is vibrating on a closed circuit then it will cut the lines of force due to the permanent magnet, and by Lenz's Law (page 237) the induced currents set up will react with the magnetic field and tend to stop the motion. The magnitude of the induced current (and hence the damping) will depend upon the value of the

resistance in circuit. For quickness of reading a tapping key is placed in parallel with the terminals of a ballistic galvanometer (page 238), so that after the first swing the coil may be quickly brought to rest by depressing the key.

It should be noted that the *steady current sensitivity is defined as the deflection in mm. of the scale per* 10^{-6} *amp. passing through the galvanometer, when the scale is* 1 *metre distant from the mirror.*

Direct Current Measuring Instruments.—Instruments which indicate the value of an electric current directly in amperes, by means of a pointer moving over a graduated scale, are known as *ammeters*. Milliammeters and microammeters are accordingly instruments constructed to measure small currents of the order of 10^{-3} amps. and 10^{-6} amps. respectively. Again the best-known type of instrument for the measurement of P.D., the *voltmeter*, utilises the principle that the current I, passing through a constant resistance R, is directly proportional to the applied voltage V. Voltmeters are, therefore, really current-measuring instruments which differ from ammeters in a certain respect to be made immediately apparent, but which from the point of view of mechanical construction are precisely similar.

Now the power consumed by a current measuring instrument may be expressed in the following alternative ways, viz. I^2R, VI or $\frac{V^2}{R}$ watts, where I is in amps, V in volts and R (the instrument resistance) in ohms. Further, since it is a fundamental principle that *any instrument placed in a circuit should absorb as small amount of energy as possible from the circuit*, then for a *given current I*, it follows that R must be kept small in order that I^2R should not be large, i.e. *ammeters must have only a very low resistance*. In consequence the P.D. (V) across an ammeter is always small and is never likely to be as great as one volt. In the case of the voltmeter, a given value of P.D. (V) is to be measured, hence the appropriate expression for the energy expended in this instrument is $\frac{V^2}{R}$ and for this quantity to be small, R must be large, i.e. voltmeters must have a high resistance. An additional significance of this latter condition is that it means the current, $I = \frac{V}{R}$, flowing through the instrument is also small. The

usual rating for good commercial instruments is 200 ω per volt, i.e. a 100 volt range voltmeter would have a resistance of 20,000 ω. In ordinary practice therefore the current passing through a good grade voltmeter can generally be neglected, but for precision work it is necessary to use instruments having still higher resistances so as to allow 1,000 ω or more per volt.

An ammeter is always placed *in series* with the rest of the electrical circuit concerned, but voltmeters, on the contrary,

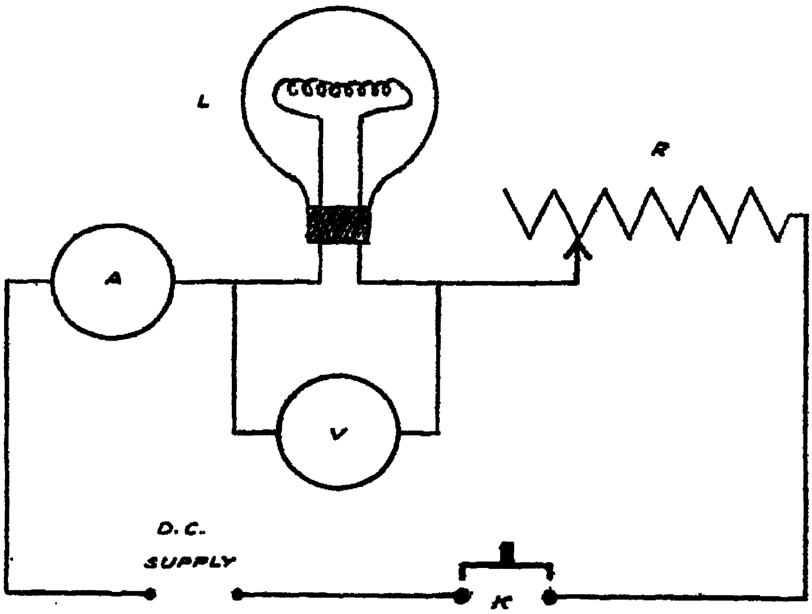


FIG. 137.

are connected *in parallel* with that part of the circuit across which the P.D. is to be measured. The meaning of these terms will become clear from a consideration of Fig. 137. In this diagram A is an ammeter connected in series with a lamp L. The ammeter thus registers the current which flows through the lamp. The terminals of the voltmeter, V, are respectively connected to those of the lamp, i.e. in parallel, and in this manner the voltmeter registers the P.D. across the lamp.

MOVING-COIL AMMETERS.—The construction of these instruments is similar to that of the moving-coil galvanometers, except in the method of suspending the coil. In Fig. 138 (*a*), I is a soft iron core, C is a moving coil consisting of a number of turns of fine insulated copper wire wound on a copper or

aluminium frame, and N and S are the soft iron pole pieces of a permanent tungsten-steel horseshoe magnet. These poles are kept in position by distance pieces AA. The moving system is supported on two short spindles with pointed ends, which act as pivots working in the jewelled bearings fixed to the non-magnetic cross-piece B. The current is led in and out of the coil by means of flat spiral phosphor bronze springs

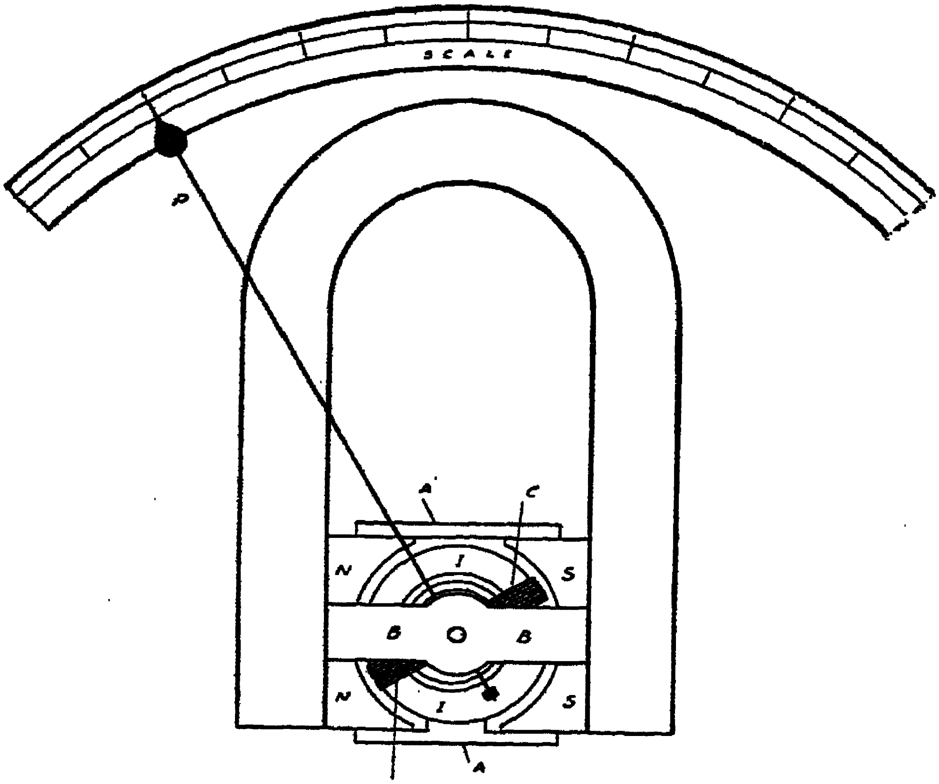


FIG. 138 (*a*).

S and S^1, which are situated respectively at the upper and lower end of the coil (the upper spring only is shown in Fig. 138(*a*)). One end of each spring is connected to a spindle, S and S^1 (Fig. 138 (*b*)), and hence to the coil, while the other ends are connected respectively to the terminals T and T^1 of the instrument. These springs are so coiled that when one is unwinding the other winds up, and so acting together, they provide the controlling couple which balances the deflecting couple produced when a current passes through the coil. Also, as in the case of a vertical torsion wire, the torsional couple is proportional to the angle of twist of one end of the wire with respect to the other, so now in this case the angle

through which the spindle turns is proportional to the couple applied to it. The free ends of the springs are attached to the spindles. It has been shown in the theory of the moving-coil galvanometer (page 183), that with the same type of magnetic field, the deflecting couple on the coil is strictly proportional to the current flowing for any position of the coil. Hence it follows that the *angular deflection of the coil is directly proportional to the current*, and so the circular scale of the instrument will be uniformly divided. Fig. 138*a* shows the details of a typical instrument of this type. The movement of the coil is damped by the induced eddy currents (page 268) set up in the metal frame upon which it is wound.

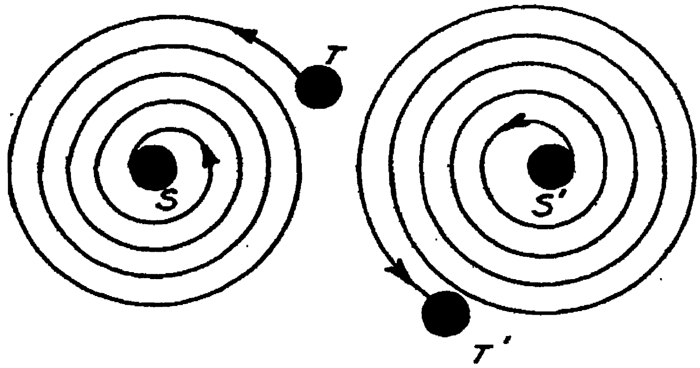


FIG. 138 (*b*).

In using the instrument care must be taken to pass the current through the coil in the direction indicated on the terminals, unless, of course, it is provided with a central zero.

As the moving coil is only wound with thin wire for the sake of lightness, the current that can be carried safely must not be greater than 0·2 to 0·25 amps., and for higher values of the current a small resistance is connected in parallel with the moving part. This resistance is referred to as a *shunt*, and has been discussed already (page 108).

MOVING-COIL VOLTMETERS.—As mentioned previously the actual mechanical movement of the moving-coil ammeter may be utilised for the voltmeter, except that in the latter the coil is wound with say 100 turns of fine copper wire compared with about 20 turns in the case of an ammeter coil. The resistance of such a voltmeter coil would be only of the order of 100 ohms, hence to obtain the desired high value of the resistance of a voltmeter it is necessary to add a high resistance in series with the coil. Another point of consider-

able importance is the question of the constancy of the calibration of these instruments, and this will be chiefly dependent upon a possible change of the various control factors with an increase of temperature. Both the strength of the control springs and the *magnetic field decrease with temperature, but acting in opposite directions these changes tend to balance one another. Hence the chief concern is the constancy of the resistance of these instruments. As mentioned above the pivoted coil is usually wound with copper wire which has a large temperature coefficient of resistance (see page 216), and in order to swamp out this undesirable feature, the large series resistance is composed of fine manganin wire, which is almost unaffected by a change of temperature. Manganin has an added advantage in possessing a high specific resistance, so that the length of wire required is reduced, and this is wound on wooden bobbins inserted in the base of the instrument between the coil and the terminals.

MOVING IRON AMMETERS AND VOLTMETERS.—This class of instrument is less sensitive than the moving coil type, but has the advantages of cheapness and lightness. In the single iron, or attraction type (Fig. 139), a piece of soft iron I is inductively magnetised as a result of the magnetic field set up by the current to be measured, which is passed through the coil CC. The piece of iron is pivoted eccentrically so that on magnetisation it will be attracted into the coil, and the pointer, P, will move over the scale. The magnitude of the deflection is controlled by a spring (as in the moving-coil instrument), or more usually by gravity as indicated in the diagram. The weight, ω_1, may be screwed along a spindle which affords a means of adjusting the zero of the instrument. The other weight, ω_2, will not exert any control when the instrument is levelled and the pointer is at zero, for the centre of gravity of the moving system will be vertically below O. If the pointer is deflected through an angle, θ, the centre of gravity of the system is displaced to the left of $O\omega_2$, and it may be shown that the restoring couple produced is proportional to sin θ. The scales of these instruments are non-uniform, and are more crowded together for the smaller readings, but the uniformity of the spacing can be varied to a

* Any slight permanent loss of field strength is adjusted by the use of a magnetic shunt incorporated in the instrument, i.e. a piece of soft-iron laid across the pole-pieces to vary the flux in the gap.

considerable extent by suitable shaping of the piece of iron, I.

The damping is effected by the use of a light piston, A (Fig. 139), fixed to the moving part, the centre of this piston travelling along the axis of the curved cylinder T. The

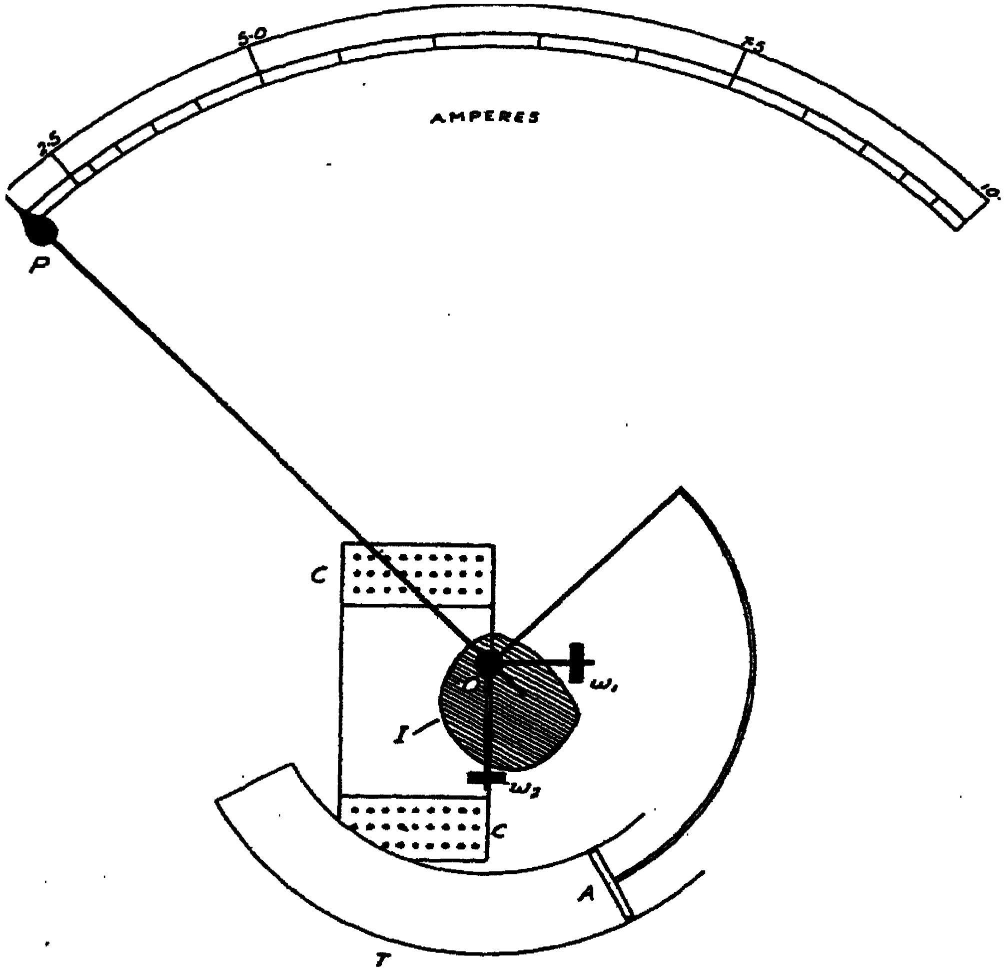


FIG. 139.

clearance between A and the tube walls is small so that the contained air may only be displaced slowly, and in this manner the system will be effectively damped.

It should be carefully noted that these gravity controlled instruments are limited principally to switchboard use as they can only be used in a vertical position.

In the double-iron, or repulsion type of soft-iron instrument the moving iron which carries the pointer, is placed near a fixed piece of iron which is inside the coil. On the passage of a current through the coil the adjacent faces of the fixed

and movable pieces of iron acquire a like polarity, so that repulsion occurs, with a consequent deflection of the pointer.

It should be evident that the action of both types of soft iron instrument is independent of the direction of current flow so that they can be used in alternating current (page 266) as well as in direct current circuits. An inherent drawback of these instruments results from the hysteresis (page 97) of the iron, namely that the descending readings of the current are generally greater than those obtained while ascending. The recent introduction of iron alloys such as mumetal or permalloy, has, however, largely overcome this difficulty. Another feature of these instruments is that the fixed coil can be made of a few turns of thick wire or strip capable of carrying 100 amps. or more, thus rendering it unnecessary to use shunts.

QUESTIONS.

1. What are the advantages and the disadvantages of (*a*) moving iron, (*b*) moving coil measuring instruments ?

A moving coil ammeter having a detachable shunt of 15/1997 ohm resistance gives a full scale deflection when a current of 10 amps. is passed through it, the potential difference across it being then 0.075 volt. What is the resistance of the instrument when the shunt is removed. and what current passing through the moving coil gives full scale deflection ? (U.L.C.I., B, 1935.)

2. Describe two distinct methods of damping indicating instruments. The resistance of the coil of a voltmeter, range 0–5 volts, is 40 ohms and the added series resistance is 460 ohms. This series resistance is removed and a shunt connected across the terminals of the instrument. Calculate the resistance of the shunt to make the instrument read as an ammeter, range 0–5 amps. (U.E.I., S2, 1932.)

3. Describe the construction of a moving coil voltmeter.

A voltmeter of 100 ohms resistance reads up to 5 volts. What resistance must be placed in series with it in order that it may read up to 20 volts ?

4. Explain briefly upon what factors the sensitivity of a galvanometer depends. Describe by means of a diagram how the use of astatic needles affects the sensitivity of a galvanometer. (C. & G., 1933.)

5. Describe the construction and the action of a tangent galvanometer, and carefully state what precautions are necessary when the instrument is being used.

CHAPTER XI

APPLICATIONS OF THE HEATING EFFECTS OF THE CURRENT

The conversion of electrical into thermal energy can be performed with ease and efficiency and this has led to many everyday applications, the most familiar of which is probably the electric lamp.

THE CARBON ARC LAMP.—If a direct current supply of about 40 volts is passed through two carbon rods which are in contact, end to end, a very high resistance is offered to the passage of the current at the contact point. In consequence there is an intense local generation of heat and the carbon is vaporised. On separating the rods the current is now conducted across the gap by means of the carbon vapour, and its passage is accompanied by the formation of a bright luminous flame between the ends of the rods. The temperature and the luminosity of the arc depend upon the magnitude of the current.

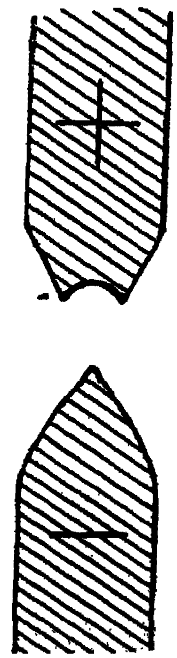


FIG. 140.

The current itself is carried across the gap by the electrons and +ve ions, and the impact of these particles with the carbon poles causes these rods to become luminous and to gradually burn away. The different appearances of the poles of the *arc* are indicated in Fig. 140. The hollow in the +ve rod is known as the *crater*, and it supplies about 85% of the total illumination and consequently is usually placed uppermost. Very refractory substances such as diamond and silica rapidly melt when placed in the crater where the temperature can reach between 3,500° C. and 4,000° C. It should be noted that the current in the arc does not obey Ohm's Law, as the *resistance decreases more rapidly than the rate of increase of*

current, and hence the arc is liable to be unstable unless a "ballasting" resistance is used in series. The carbon arc lamp is still used for projection purposes, e.g. in searchlights, where as small a source as possible is desirable, and is obtained in the case of the Sperry searchlight by cooling the carbons with a blast of air or alcohol spray to restrict the area of the crater.

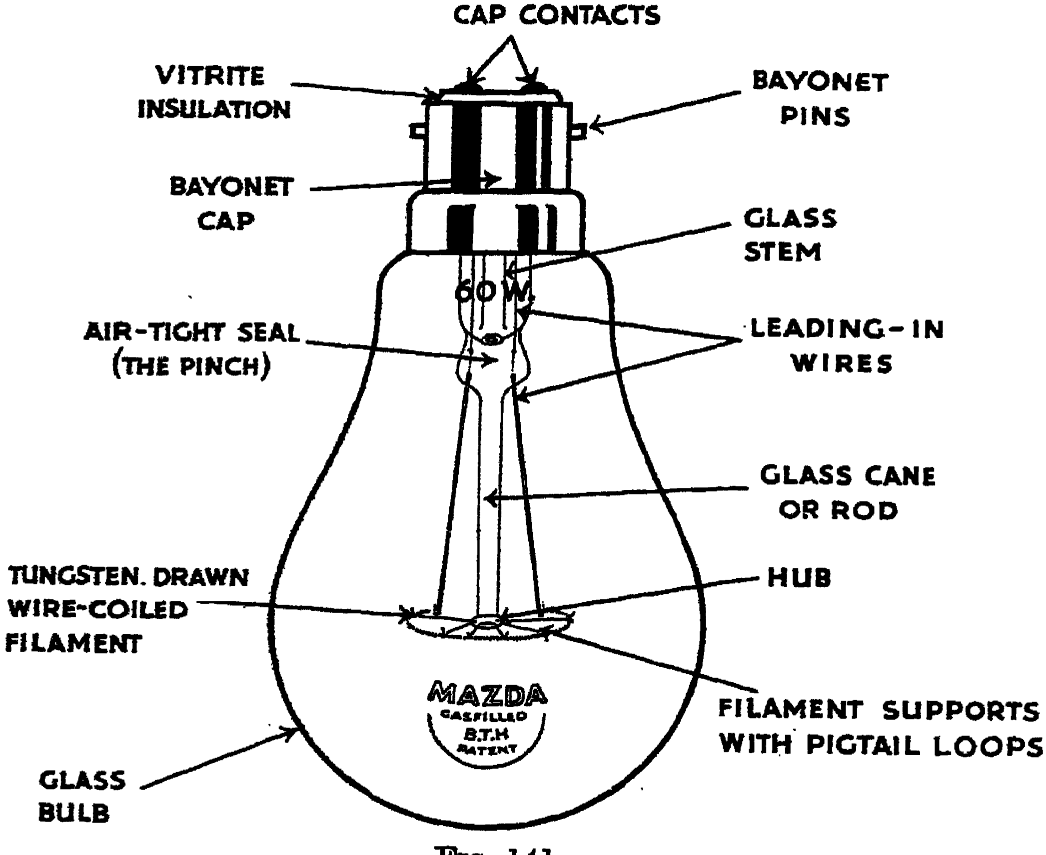


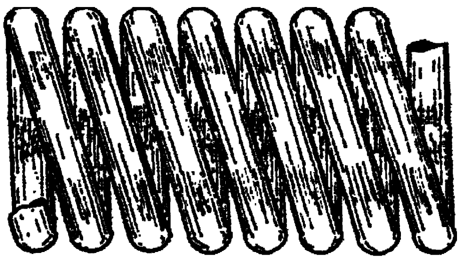
FIG. 141.

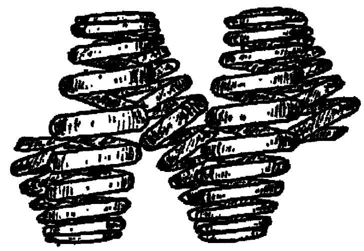
THE INCANDESCENT LAMP was invented by De Moleyns in 1841 and consisted of a platinum wire enclosed in an evacuated bulb. The wire was heated to incandescence by an electric current. Platinum was substituted first by carbon and later by osmium and tantalum filaments, but at the present day tungsten is almost universally employed as the filament.

CARBON FILAMENT LAMP.—This type of incandescent lamp was first produced in 1880 by Edison and Swan, who were working independently. The carbon filament is now obtained by heating the fine threads formed by forcing a solution of cellulose in zinc chloride through a suitable die. The lamps

are very inefficient for illuminating purposes, as only 3% of the energy supplied is available in the form of light; they are primarily used to-day as resistances for various testing purposes.

METAL FILAMENT LAMP.—At temperatures above 1,300° C. the carbon filament volatilises, with the consequent blackening of the bulb, but by using a fine tungsten wire the temperature may be raised to 2100° C. Above this temperature particles of the filament are liberated and become deposited on the interior of the bulb. This trouble was overcome by the distinguished American physicist, Irving Langmuir, in 1913, and the procedure adopted was to fill the lamp bulb with a small amount of an inert gas such as nitrogen or neon.





(*a*) FIG. 142. (*b*)

The filament of a **gas-filled lamp** can be "run" at 2,500° C., when the light emitted is a nearer approach to "white" light. A further difficulty arises, however, from the cooling of the filament by convection currents in the gas, which is minimised by winding the wire in a very close spiral and placing the latter horizontally in a pear-shaped bulb with a narrow neck (Fig. 141). A very recent improvement in the efficiency of the filament lamp is the "**coiled-coil**" lamp, in which the tungsten wire (Figs. 142 (*a*) and (*b*)) is initially coiled in the same way, but on a smaller radius, as the ordinary filament. This coil is then wound once again on a considerably larger radius, so that a much shorter and thicker coil is obtained. In this way the area effectively exposed to the cooling action of the gas is reduced, and thus the filament can be run at a higher temperature to give a greater brilliance.

The gas-filled lamp is often indiscriminately referred to as the "*half-watt*" lamp, inferring that the rate of consumption of energy is $\frac{1}{2}$-watt per candle power, but actually it is usually *higher* than this value.

Efficiency.—The efficiency of an incandescent lamp is usually defined as the number of watts consumed for each candle power (c.p.) of light supplied or

$$\textbf{Efficiency} = \frac{\textbf{Watts consumed by the lamp}}{\textbf{C.P. of the lamp.}}$$

Thus a 60-watt lamp giving 40 c.p. has an efficiency of $\frac{60}{40} = 1{\cdot}5$ watts per c.p.

Measurement of the Efficiency of a Lamp.—In order to measure the efficiency of a lamp it is clearly necessary to determine the watts consumed by it, as well as the c.p. of the light that it furnishes.

Instruments which are used for measuring illuminating powers are known as **photometers,** and a simple but efficient type of photometer is that due to Bunsen. In this photometer a grease-spot S is placed on the centre of a sheet of paper which is fixed in a vertical position. The standard lamp L_1 of known c.p. and the lamp L_2 under test, are placed on opposite sides of the screen. The position of one of the lamps L_2, say, is adjusted until the grease spot becomes indistinguishable from the rest of the paper, and in this position the illumination due to lamp L_1 at S = the illumination due to lamp L_2 at S. If d_1 and d_2 are the respective distances of the two lamps L_1 and L_2 from the screen, then the following relation holds :

$$\frac{\text{C.P. of lamp } L_1}{\text{C.P. of lamp } L_2} = \frac{d_1^2}{d_2^2}$$

$$\text{or C.P. of lamp } L_2 = (\text{C.P. of lamp } L_1)\,\frac{d_2^2}{d_1^2}$$

It should be noted in the preliminary adjustment of the position of the lamp L_2, that when the screen is viewed from the side of greater illumination, the grease spot will appear darker than the rest of the paper. Conversely from the side of lesser illumination the spot will appear brighter than the surrounding paper. If the lamps to be compared differ in colour, the exact setting of the photometer becomes very uncertain.

To determine the watts consumed by the lamp, it is connected in series with an ammeter, A, and a rheostat, R, in

a circuit as shown in Fig. 137 (page 185). A voltmeter, V, is also connected to the terminals of the lamp. Then

if I=ammeter reading and V=voltmeter reading

$$\text{Watts consumed} = I \times V.$$

From the data obtained, viz. the c.p. of the lamp and the watts consumed by it, its efficiency can be calculated.

Experiment.—By means of the rheostat, R, vary the current flowing through the lamp, and use the Bunsen photometer to measure its light efficiency for different values of the power consumed by it. Commence the experiment with all the resistance in circuit and gradually increase the value of the current. Tabulate your results as follows:

Ammeter Reading (I)	Voltmeter Reading (V)	Watts $= I \times V$	C.P.	Efficiency $= \frac{\text{Watts}}{\text{C.P.}}$

Plot a graph showing how the efficiency varies with the watts consumed.

THE MERCURY VAPOUR ARC LAMP.—The incandescent body in this type of lamp is a long column of mercury vapour, which is contained in a glass vacuum tube supplied with electrodes at each end. During the last few years a "high-pressure" (i.e. 1 atmosphere or more) type of mercury vapour discharge lamp (Fig. 143) has been evolved suitable for large scale lighting, and its light efficiency is at least three times as large as an ordinary gas-filled lamp. The mercury vapour arc lamp is a most powerful source of ultra-violet radiation, which has found considerable application in radio-therapy. In this method of

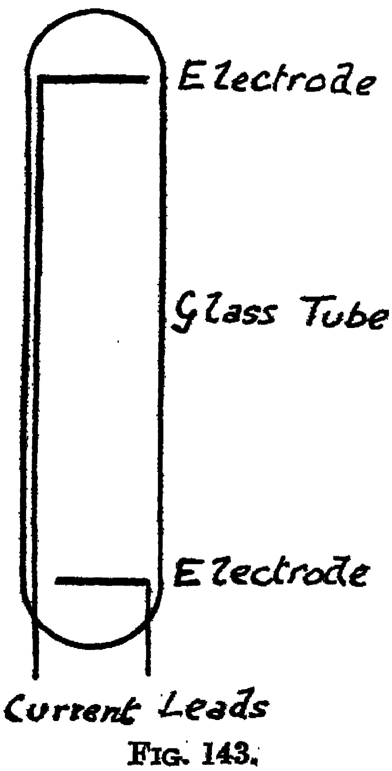


FIG. 143.

treatment for certain diseases the human body is exposed to the source of ultra-violet radiation.

THE NEON LAMP.—This lamp consists of an evacuated bulb containing a small amount of neon gas (at about 10 mm. of mercury pressure) and generally in addition about 20% of helium and a little hydrogen. The two electrodes vary considerably in their form, but in most commercial lamps the area of one electrode is much less than that of the other, and the lamps exhibit rectifying (see page 258) properties. In Fig. 144 a "beehive" type is shown, in which one electrode is an iron disc placed within, and at the base of a "beehive," the latter electrode consisting of a suitably coiled length of wire.

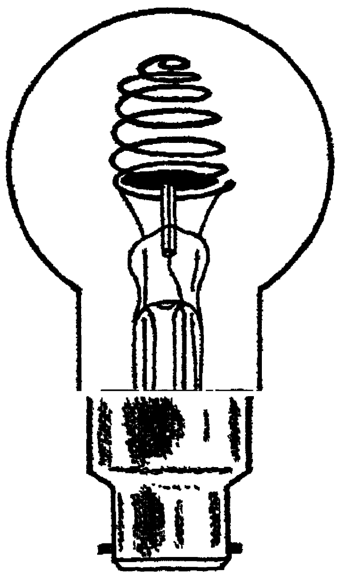


FIG. 144.

The current passes through the gas by means of the ionised gas molecules (page 35), but the process of conduction does not start until a definite minimum voltage, the sparking potential, has been applied, its value being dependent upon the pressure of the gas. The discharge glows with a brilliant orange-red light, which is used extensively for advertising purposes, for fog-light beacons at aerodromes, and for pilot and indicator lights on electric cookers, etc. The student should perform the following simple experiment:

Experiment.—Connect a commercial neon lamp to the 200 volts (or more) D.C. mains in such a way that the larger electrode is covered with an "orange-yellow glow." This fact indicates that this electrode is now the cathode of the discharge tube, i.e. the electrode where the current leaves the lamp and is the one which is therefore connected to the negative pole of the mains (this latter fact can be verified by other means, of course). Reverse the connections to the supply. The glow will now appear on the smaller electrode, hence the lamp may be employed to find the polarity of the mains. It is interesting to note that the dark space between the "negative glow" and the surface of the cathode is known as Crookes' Dark Space, named after its discoverer, the English scientist Sir William Crookes. The dark space between the anode and the negative glow is known as the Faraday Dark Space.

The rectifying property of a neon lamp arises from the fact that the *current passing through a discharge tube is normally proportional to the area of the negative glow.* Consequently when the larger electrode is the cathode a bigger current will pass than when the smaller electrode is the cathode.

The rays from a neon tube are particularly valuable for the irradiation of plants, as a much greater quantity of carbohydrates are formed in the plant leaves under the action of red light, than say green light of the same intensity.

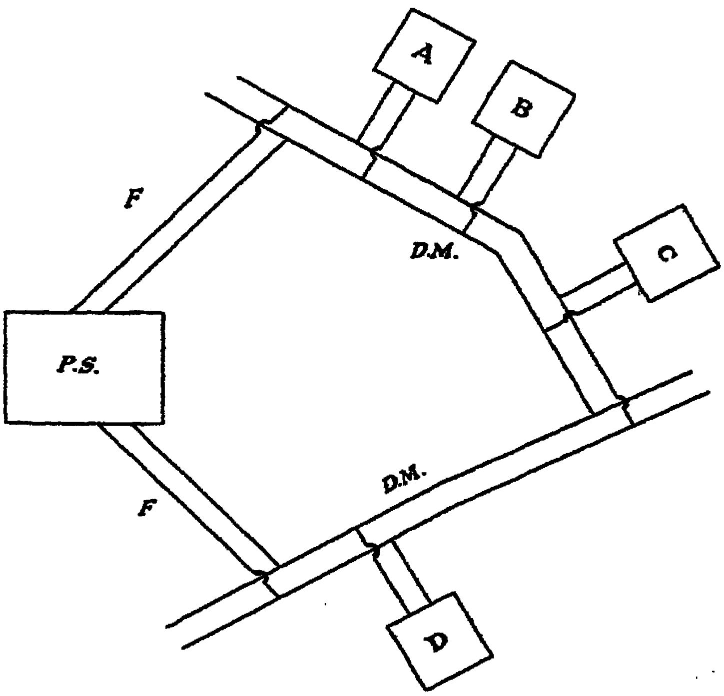


FIG. 145.

ELECTRIC LIGHTING.—The current for the lighting of buildings is obtained usually from electric supply mains. These distributing mains (D.M. in Fig. 145) obtain their power from the power station (P.S.) by means of 2-wire feeders (F). The mains are laid underneath the streets, and tappings are made to supply the various consumers A, B, C, D, etc. The electric supply at the power station is obtained from machines known as *dynamos* (page 260), and their purpose is to convert mechanical into electrical energy.

The chief features of a house lighting system are (*a*) the cables and wires, (*b*) fuses, (*c*) lamps and domestic appliances, and (*d*) the meters.

(*a*) The cables and wires in electric lighting circuits are always made of copper which is a much better conductor than iron. It also has a high ductility, i.e. it can be easily drawn out into a wire. A conductor which consists of one strand only is referred to as a *wire*, while a conductor comprising more than one strand is termed a *cable*. The usual number of strands used in the manufacture of cables is 3, 7, 19, 37, 61 and 91. The conductors are insulated with rubber, gutta-percha or impregnated paper. The number of strands used in any particular cable is determined by the current that it is intended to carry.

Electric lamps are always connected in parallel when used for lighting a building. This method has obvious advantages over the series arrangement. When the lamps are connected in parallel and one lamp breaks down the other lamps are not put out of circuit, whereas in a series arrangement a break in one lamp would stop completely any current passing. Furthermore, a parallel arrangement necessitates a much lower potential difference at the mains than does a series arrangement.

It is evident that the voltage (V_1) supplied to a consumer is always less than that (V_2) delivered at the terminals of the dynamo, owing to the potential drop in the intervening cables. If R be the total resistance of the cables and leads, and I is the current flowing at any particular time, then $V_2=V_1+IR$. Furthermore, the loss of energy in the cable will be given by I^2R and obviously for the maximum efficiency of transmission of power, this quantity must be a minimum. Now if P denotes the *given* power to be transmitted, then $P=IV_1$ or $I=P/V_1$ and therefore the cable losses may be written as $\frac{P^2}{V_1^2}R$. Hence these losses will be a minimum when R is small or V_1 is large. Both these requirements entail increased cost, in the first case a bigger cross-section of conductor is necessary, while with higher voltages superior insulation of the cables will be imperative. In practice it is found that the latter of these two alternatives is more economical.

(*b*) Fuses are the " safety-valves " of electrical circuits and are inserted to prevent too large a current from flowing through them. In brief the function of a fuse is that of a " cut-out," and for currents up to about 30 amps. the fuse wire is usually of lead or tin (or a tin-lead alloy). The wire is held in suitable

brass clips fixed to a porcelain base (the latter providing both electrical insulation and also protection against fire), and its gauge is chosen, so that when through a defect in the circuit the current reaches a predetermined safety limit, the extra heat generated is sufficient to cause fusing. For main circuits a *mechanical* circuit-breaker is generally employed. Small electric flashlamp bulbs are inserted in the —ve leads of the H.T. batteries in wireless circuits to act as fuses.

(*c*) The lamps employed in lighting circuits are usually vacuum or gas-filled incandescent lamps, and they are designed to operate at the various standard voltages.

(*d*) The various types of energy meters will be discussed later.

Example.—A direct current generator which operates at 400 volts supplies a current of 45 amps. to a factory, through a line having a resistance of 2.1 ohms. Determine (1) the power developed by the generator, and (2) the voltage at which the factory receives its electric supply.

Power developed by generator

$$=45\times400 \text{ watts}$$
$$=18{,}000 \text{ watts}$$
$$=18 \text{ k.w.}$$

By Ohm's Law the potential drop along the line

$$=R\times I$$
$$=2.1\times50$$
$$=105 \text{ volts.}$$

Hence the factory receives its electrical energy at a voltage of $400-105=295$.

DOMESTIC APPLIANCES.—The demand for these appliances is increasing rapidly with the ever-growing use of electrical power. In general the heating element carrying the current usually consists of a high resistance wire (or strip) made of nickel-chromium alloy, which has a high electrical resistance and does not oxidise at red-heat.

Electric Fires.—In electric fires the heating elements are wound on fireclay insulators in the form of spirals, so that they occupy only a minimum of space. The heated wires give rise to convection currents in the air, and they are so arranged that the heat is dispersed over as wide an area as possible.

The Electric Kettle.—This appliance is furnished with two "bottoms," the heating element being placed between them, but is insulated by means of sheets of mica. The kettle is normally made of polished copper or nickel plate and is mounted on heat-insulated feet. The efficiency of a good electric kettle is between 85% and 90%, while that of an ordinary gas ring is usually below 60%.

The Electric Iron.—In this case the heating element is so distributed that a uniform temperature is established all over the iron sole. The element is electrically insulated from the sole, but the best possible thermal contact is maintained

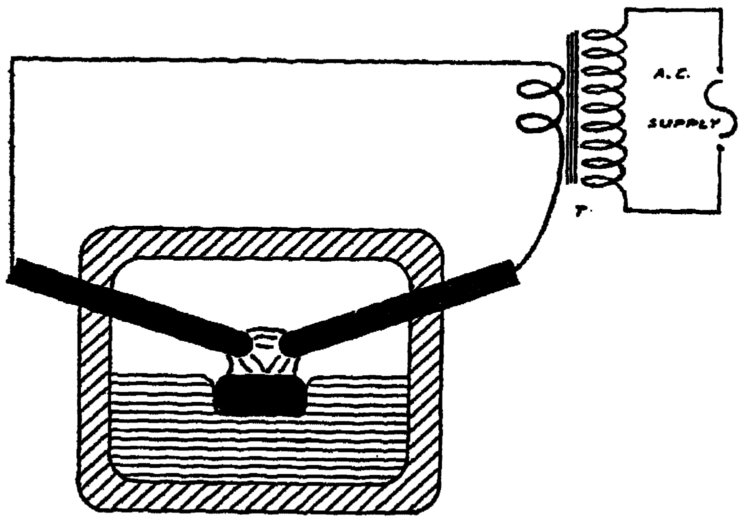


FIG. 146.

between them, and the sole transfers the heat to the fabric by conduction.

OTHER APPLIANCES.—*Electric furnaces* are of two kinds. In *resistance* furnaces the heat is obtained by the passage of a current through wire wound in grooves on an insulator.

In the other type which is known as the *arc furnace,* the high temperature is obtained by means of an electric arc which is caused to play in the region where the heat is required. A typical example of this class of furnace is shown in Fig. 146. Since currents of the order of 10,000 amperes are necessary, the power is obtained from the secondary of a step-down transformer T (page 250), using the A.C. supply.

Electrical Resistance Welding.—In this process a strong electric current is passed across the junction of the two pieces to be welded together. Although the contact resistance

between the metals is itself low, it is much greater than that of the rest of the circuit (note the single turn S of the secondary winding of the transformer PS in Fig. 147), consequently there is an intense local development of heat. The junction, W, is heated quickly to the welding temperature, and the pieces are then mechanically forced together.

In *arc welding* an electrode of carbon or metal is fitted with an insulating handle, and connected to a specially designed direct current generator. The position of the electrode is adjusted until an arc is struck between it and the metal to be welded.

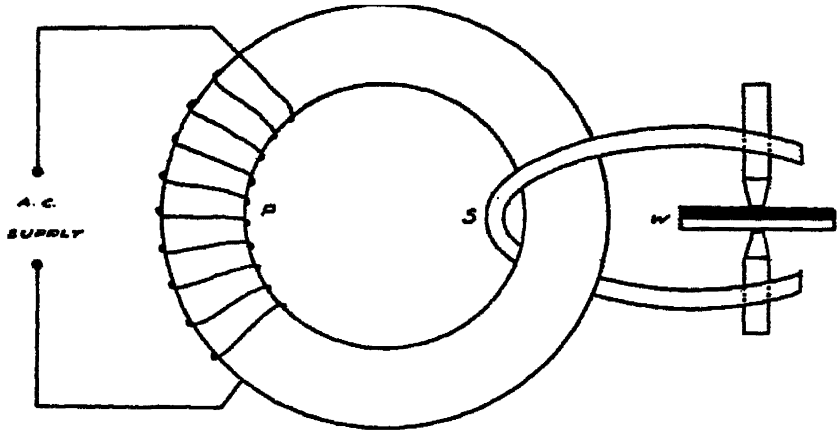


FIG. 147.

The intense heat of heavy carbon arcs is also utilised for the *cutting* of metal tubes.

Various articles of wearing apparel are frequently electrically heated when worn by airmen flying at high altitudes. In this case flexible resistance strips are sewn into the garment, and the ends are joined to a suitable electrical supply.

Example.—A heating appliance is fitted with two elements each of resistance r ohms. Compare the degrees of heating obtained when the appliance is connected to the mains and the current passes (1) through one element only, (2) through the two elements when they are connected in series, and (3) through the two elements when they are connected in parallel.

Let V volts be the potential drop at the mains.

(1) When the current passes through one element only.

Let I_1 be the value of the current,

$$\text{Then } I_1 = \frac{V}{r}$$

$$\therefore \text{Heat developed in one second } (H_1) = I_1^2 r = \frac{V^2}{r^2} \cdot r$$

$$= \frac{V^2}{r} \text{ joules.}$$

(2) When the current passes through the two elements connected in series.

Let I_2 be the value of the current.

$$\text{Then } I_2 = \frac{V}{2r}$$

$$\therefore \text{Heat developed in one second } (H_2) = I_2^2 r = \frac{V^2}{4r^2} 2r$$

$$= \frac{V^2}{2r} \text{ joules.}$$

(3) When the current passes through the two elements connected in parallel.

Let I_3 be the value of the current flowing through each element.

$$\text{Then } I_3 = \frac{V}{r}$$

$$\therefore \text{Heat developed in each element} = I_3^2 r$$

$$= \frac{V^2}{r^2} . r$$

$$= \frac{V^2}{r} \text{ joules.}$$

$$\therefore \text{Heat developed in the two elements } (H_3) = \frac{2V^2}{r} \text{ joules.}$$

$$\therefore H_1 : H_2 : H_3 = \frac{V^2}{r} : \frac{1}{2}\frac{V^2}{r} : \frac{2V^2}{r}$$

$$= 2 : 1 : 4$$

QUESTIONS.

1. Describe carefully how you would determine the efficiency of an electric lamp.

2. Describe briefly the main features of the lighting system of a house. Why are the lamps always connected in parallel rather than in series?

3. Compare the construction and the efficiencies of the several types of filament lamps. Describe a recent development in the construction of gas-filled lamps and explain its object. (U.E.I., S2, 1935.)

4. Give a short account of various domestic appliances in which electrical heating is utilised.

5. Describe the process of electric welding.

CHAPTER XII

ELECTRICAL MEASUREMENTS

MEASUREMENT OF RESISTANCE.—The four principal laboratory methods of measuring resistance are (1) the ammeter-voltmeter method, (2) the method of substitution, (3) the Wheatstone bridge method, and (4) the potentiometer method.

THE AMMETER-VOLTMETER METHOD.—This is a direct application of Ohm's Law. The potential difference across the unknown resistance R is measured by a voltmeter, V, and the current passing by an ammeter A, whence

Resistance=Voltmeter Reading÷Ammeter Reading.

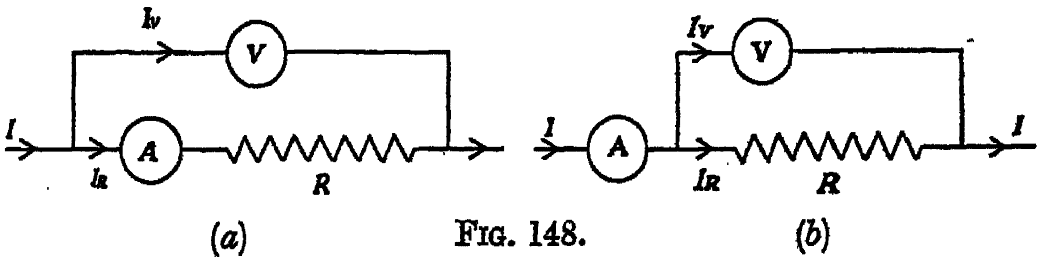


FIG. 148.

There are two alternative methods of connection to be considered, however, viz. (*a*) and (*b*) in Fig. 148. In order to ascertain the preferential method of connection, consider a particular case where $R=400\omega$, the voltmeter resistance $(R_V)=1{,}000\omega$, the ammeter resistance $(R_A)=5{\cdot}0\omega$, and the current (I) passing in the *main* circuit is 0·05 amps. Let I_V and I_R denote the currents passing through the voltmeter and resistance respectively.

Case (*a*).—By Ohm's Law it follows that

$$I_V \times R_V = I_R\,(R_A+R)$$

$$\text{or } \frac{I_V}{I_R}=\frac{405}{1000} \qquad \qquad (1)$$

$$\text{But } I_V+I_R=I=0{\cdot}05 \text{ amps.} \qquad \qquad (2)$$

Hence from (1) and (2) it is easily found that

$$I_R = \frac{10}{281} \text{ amps. and } I_V = \frac{405}{28100} \text{ amps.}$$

$$\therefore V \text{ (the voltmeter reading)} = I_V \times R_V = \frac{405}{28100} \times 1{,}000$$

$$= \frac{405}{28{\cdot}1} \text{ volts}$$

It follows that

$$R + R_A = \frac{V}{I_R} = \frac{405}{28{\cdot}1} \div \frac{10}{281} = 405\,\omega$$

i.e. $R = 405 - R_A = 400\omega$, which is, of course, the correct value of the resistance.

Case (*b*).—Proceeding as in the previous case it is found

$$\text{that } \frac{I_V}{I_R} = \frac{400}{1000}$$

$$\text{and hence } I_V = \frac{1}{70} \text{ amps. and } V = \frac{1000}{70} \text{ volts.}$$

But in this case the current registered by the ammeter is that passing in the main circuit, i.e. 0·05 amps.

$$\therefore R = \frac{\text{Voltmeter Reading}}{\text{Ammeter Reading}} = \frac{1000/70}{0{\cdot}05} = 285{\cdot}7\omega,$$

which shows a considerable divergence from the true value.

It should be noted, of course, that in connection (*a*) the resistance of the ammeter was assumed to determine R, but it is evident that the error involved if this was unknown is negligible compared with the error involved in the (*b*) connection. Hence the (*b*) method of connection is quite inaccurate for the measurement of resistances comparable in magnitude with that of the voltmeter itself, for in these cases the current flowing through the voltmeter is comparable with that flowing through the resistance, and the ammeter records the sum of these currents.

If the resistance R is relatively small compared with R_V, then the error involved in using the (*b*) connection is much less, e.g. if $R = 40\omega$ it can be shown as above that the

$$\text{ratio } \frac{\text{Voltmeter Reading}}{\text{Ammeter Reading}} = 38{\cdot}5\,\omega.$$

The ammeter-voltmeter method of measuring resistance is very useful for approximate determinations and is in general use in electrical engineering.

THE METHOD OF SUBSTITUTION.—In this method the unknown resistance X (Fig. 149 (*a*)) is placed in a circuit containing a tangent (or pointer) galvanometer (T.G.), a battery, E, variable resistance box, R, and a plug key. With *b* and *d* connected the galvanometer deflection is noted. The circuit is now broken and then made again between *c* and *d*, the resistance in R being initially made large to avoid the possibility of over-deflecting the galvanometer. R is now adjusted until the galvanometer deflection is the same as previously, when the value of R will be the measure of the unknown resistance X. If a plug key is not available an alternative circuit is shown in Fig. 149 (*b*), making use of a tumbler electric light switch, S_1S_2. When the switch knob is down the two connecting points S_1 and S_2, are bridged by the copper connecting strip of the switch so that the unknown resistance X is short-circuited, and therefore virtually removed from the circuit. With the switch in this position the resistance R is adjusted to give a suitable deflection, and the magnitude of R is carefully noted. The knob of the switch is now raised so that X is brought into the circuit and R is again adjusted so that the same galvanometer deflection as previously is obtained. The value of X will now be equal to the *difference* in the values of R in the two experiments.

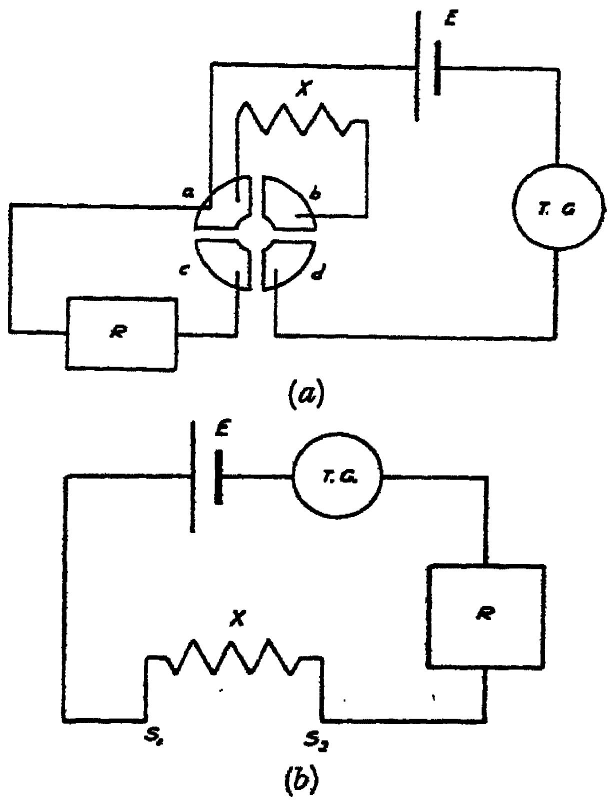


FIG. 149.

If the value of X is large the tangent galvanometer may be conveniently replaced by a more sensitive galvanometer or a milliammeter.

THE WHEATSTONE BRIDGE.—This is by far the most satisfactory of the ordinary methods of measuring resistance. The arrangement was devised originally by Professor Hunter Christie of the Royal Military Academy, Woolwich, and was later popularised by Professor Wheatstone. Charles Wheatstone started life as a manufacturer of musical instruments, but later became Professor of Physics at King's College, London.

The bridge consists essentially of four resistances, R_1, R_2, R_3 and R_4 (Fig. 150), arranged so that two series groups are in parallel with one another. A battery, E, is connected between the common terminals, A and B, of these groups, while a galvanometer, G, and key, K, are inserted between the junctions C and D. Let R_1 and R_2 be chosen so that the ratio $\frac{R_1}{R_2} = n$ say, is known.

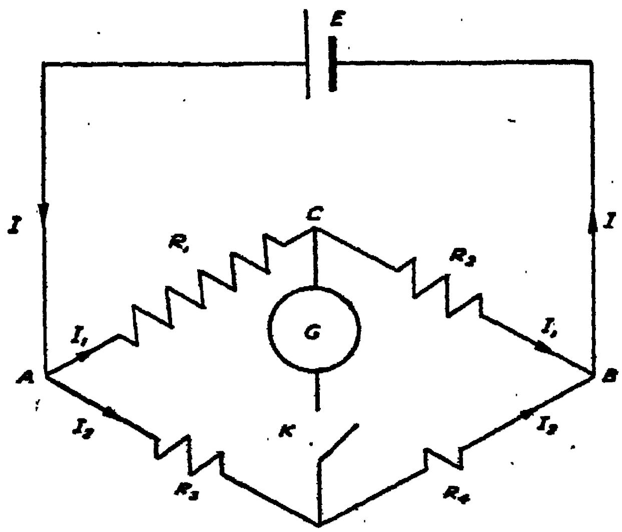


FIG. 150.

Again R_4 is the unknown resistance and therefore fixed, so that R_3 is the adjustable resistance. Now if I_1 and I_2 are the currents flowing in the arms ACB and ADB respectively, then the following results are evident by Ohm's Law.

The P.D. from A to $C = I_1R_1$
The P.D. from A to $D = I_2R_3$

Now if the value of R_3 is chosen so that the P.D. between A and C is equal to the P.D. between A and D, i.e. $I_1R_1 = I_2R_3$, then C and D must be at the same potential since A is a common point.

If this condition has been realised, then on depressing the key in the galvanometer circuit no current will flow through the instrument. Furthermore, since the P.D. between A and B is given either by $I_1 (R_1+R_2)$ or $I_2 (R_3+R_4)$ it immediately follows that $I_1R_2 = I_2R_4$, since $I_1R_1 = I_2R_3$.

Combining the two relations the condition for the *balance* of the bridge is that

$$\frac{I_1R_1}{I_1R_2} = \frac{I_2R_3}{I_2R_4}$$

$$\text{i.e.}\ \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

$$\text{But}\ \frac{R_1}{R_2} = n \text{ and hence } R_4 = \frac{R_2}{R_1}.R_3 = \frac{R_3}{n}$$

The two *arms*, AC and CB, of the bridge, containing the resistances R_1 and R_2 respectively, are known as the *ratio arms*.

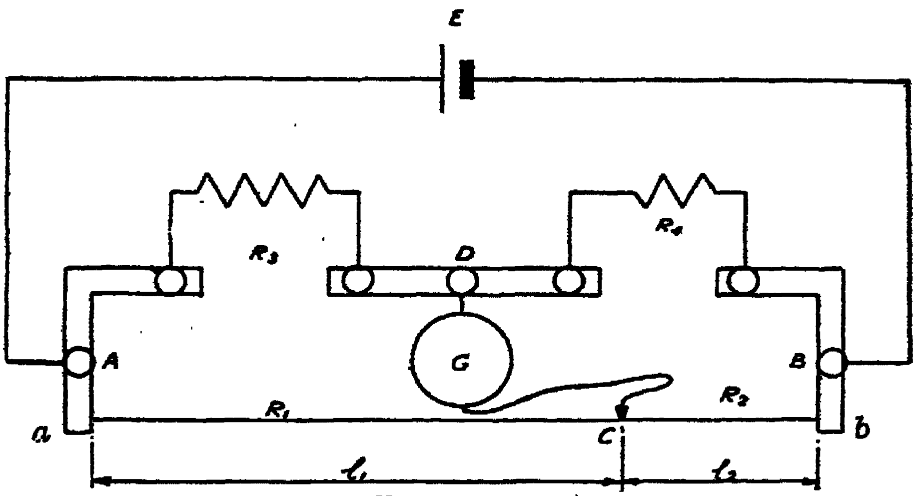


FIG. 151.

THE METRE BRIDGE.—This is the simplest form of Wheatstone Bridge and consists of a uniform wire *ab* (usually 1 metre or ½ metre in length), soldered to the L-shaped ends of a copper bar (shaded in Fig. 151) which has two gaps in its length. The unknown resistance R_4 and a resistance box (or fixed resistance), R_3, are respectively inserted in these gaps. The lettering of the figure is made to correspond with that of Fig. 150, and it is to be assumed that the resistance of the copper bar is negligible.

The resistance R_3 having been fixed, the adjustable contact C is moved along and the wire is tapped at a succession of points until the galvanometer is undeflected. In this position the condition holds that $R_4 = \frac{R_2}{R_1}.R_3$. Now the bridge wire *ab* is uniform, and hence its resistance per unit length is constant and equal to *r* ohms, say.

$$\therefore\ R_2 = l_2 r \text{ and } R_1 = l_1 r.$$

$$\text{Hence } \frac{R_2}{R_1} = \frac{l_2 r}{l_1 r} = \frac{l_2}{l_1}$$

It follows that $R_4 = \frac{R_2}{R_1} . R_3 = \frac{l_2}{l_1} . R_3 = \frac{(100 - l_1)}{l_1} . R_3$

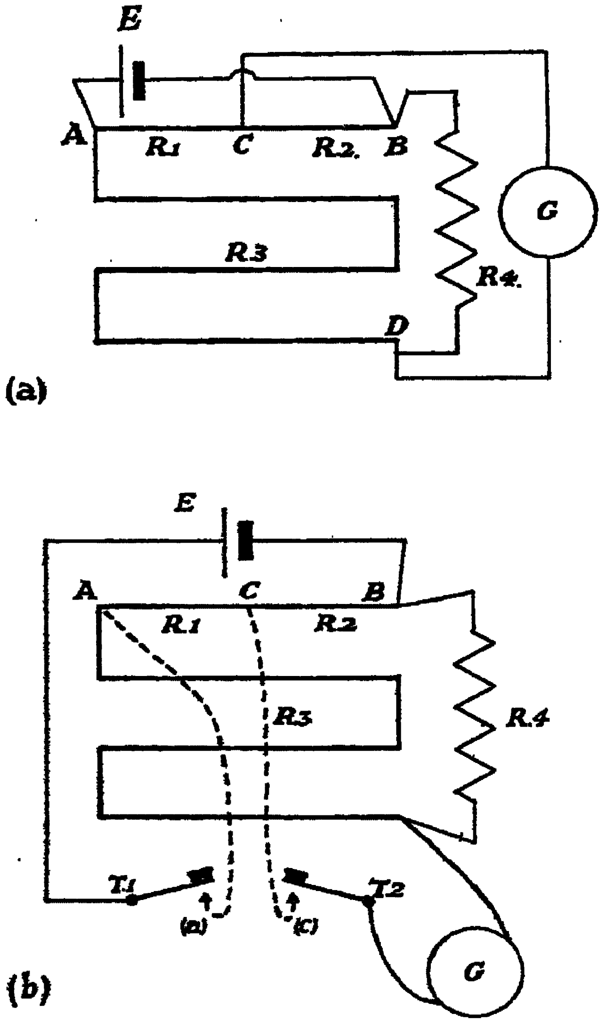


FIG. 152.

if the wire is 100 cms. long and l_1 is measured in cms.

THE POST OFFICE BOX.—This is a commercial form of the Wheatstone Bridge to enable resistances to be measured rapidly. It consists of a number of coils of known resistance (see Figs. 152 (*a*) and (*b*)), which form three arms of the bridge, while the fourth arm consists of the resistance R_4, which is to be measured. The lettering in Fig. 152 (*a*) conforms with that of Fig. 150, so that it is easily seen that when balance is obtained

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

In order to avoid the necessity of keeping the battery and galvanometer in the circuit during the whole of the time that measurements are being made, two tapping keys, T_1 and T_2 (Fig. 152 (*b*)) are fixed to the ebonite cover of the box.

The connections for these keys vary in different types of boxes. In the pattern shown, the galvanometer terminal C is connected by a strip (shown dotted in Fig. 152 (*b*)) inside the box to the stud *c*, and the battery terminal A is similarly connected to *a*. When the keys, T_1 and T_2 are depressed, the

battery and galvanometer are respectively put in circuit. The battery key should always be depressed before the galvanometer key, to avoid possible inductive effects (Chap. XIII).

The ratio arms AC and CB each consist of three coils of 10, 100 and 1,000 ohms respectively so that ratios $\frac{1000}{100}$, $\frac{1000}{10}$, $\frac{100}{1000}$ and $\frac{10}{1000}$ $\left(\text{as well as } \frac{10}{10}, \frac{100}{100} \text{ or } \frac{1000}{1000}\right)$ can be obtained between them. The arm AD consists usually of coils of resistances varying from 1 to 5,000 ohms, so that by the use of the ratio arms it is possible to use the P.O. box to measure resistances ranging from 0.01 to 1,111,000 ohms. The P.O. box is unsuitable for the accurate measurement of low resistances, and it is most sensitive when the unknown resistance and the resistances of the ratio arms are of the same order of magnitude.

The following example will illustrate the method of using the bridge to measure a resistance.

Suppose the coil whose resistance is to be measured has been placed in the fourth arm of the box, and the resistances R_1 and R_2 are each made equal to 10 ohms. An approximate balance is obtained by taking out plugs in the arm AD. Suppose that in this manner the resistance R_3 is found to lie between 15 ohms and 16 ohms. The 100 ohm coil is next inserted in AC in place of the 10 ohm coil, and the nearest balance possible is again obtained. The resistance in the arm AD will now lie between 150 ohms and 160 ohms. Suppose that 153 ohms is too small and that 154 ohms is too large. The resistance R_3 clearly lies between 15.3 ohms and 15.4 ohms. The 100 ohm coil in AC is now replaced by the 1,000 ohm coil and, proceeding as before, the value of R_3 can be obtained correct to two decimal places.

Experiment.—Use the P.O. box to determine the value of, say, a 25,000 ohms wireless resistance. In this particular case R_1 and R_2, the ratio arms, should be made equal to 100 and 1,000 ohms respectively.

THE POTENTIOMETER METHOD OF MEASURING LOW RESISTANCES.—The previous methods reviewed are not suitable for the measurement of low resistances, but with this method great accuracy is obtainable. The theory of the potentio-

meter is dealt with on page 227, to which reference should be made.

In Fig. 153 PQ is the potentiometer wire, and T the adjustable contact. The unknown resistance X is connected in series with a standard low resistance S, an adjustable resistance R, an accumulator E, and an ammeter, A, which is to act as an approximate indicator of the current (I) flowing in the circuit.

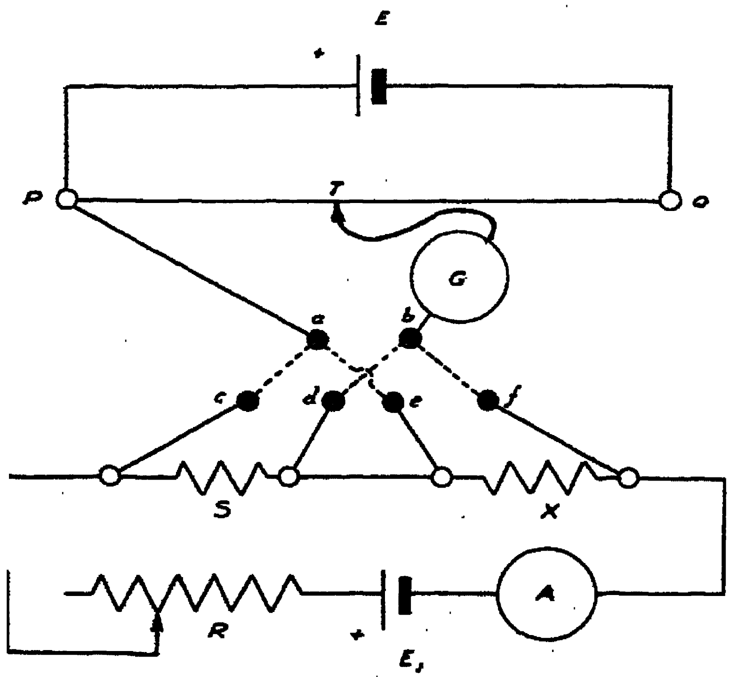


FIG. 153.

With a and b respectively connected to c and d and hence to the ends of S, balance the potentiometer. Let $PT = l_1$.

$$\text{Then } \frac{\text{P.D. across S}}{\text{P.D. across PQ}} = \frac{l_1}{\text{length PQ}} \quad . \quad (1)$$

Now connect a and b to e and f respectively and determine the P.D. across the unknown resistance X. If PT is now equal to l_2

$$\text{Then } \frac{\text{P.D. across X}}{\text{P.D. across PQ}} = \frac{l_2}{\text{length PQ}} \quad . \quad (2)$$

Combining (1) and (2) it is easily seen that

$$\frac{\text{P.D. across X}}{\text{P.D. across S}} = \frac{l_2}{l_1} \quad . \quad . \quad . \quad (3)$$

But if X and S are the resistances in ohms and I is the current flowing through them, then by Ohm's Law the P.D. across X=I.X and the P.D. across S=I.S.

$$\text{i.e. } \frac{\text{P.D. across X}}{\text{P.D. across S}}=\frac{\text{I.X}}{\text{I.S}}=\frac{\text{X}}{\text{S}} \quad . \quad . \qquad (4)$$

From (3) and (4) it is evident that

$$\frac{X}{S}=\frac{l_2}{l_1}$$

$$\text{or } \mathbf{X}=\frac{\mathbf{l_2}}{\mathbf{l_1}}.\mathbf{S}$$

Specific Resistance.—The resistance of a conductor is found to vary directly as its length, l, for if the length of a uniform resistance wire is exactly doubled or trebled, its total resistance is also increased to two and three times respectively.

Now consider two wires of equal cross-sectional area, A, and resistance r connected in parallel, then the combined resistance $R=r/2$. These two wires, however, may be replaced by a single wire of double the cross-section, whence it is apparent that doubling A has decreased the resistance by $\frac{1}{2}$, or the resistance of a uniform wire is proportional to $\frac{1}{\text{area of cross-section}}$. In other words an electric current will flow more easily through a thick than through a thin conductor (since $I \propto \frac{1}{R} \propto A$ for a constant applied P.D.), which is comparable to the fact that a capillary tube (i.e. a tube of narrow bore) offers a greater resistance to the passage of water than does a wide bore tube.

In general, therefore, $R \propto \frac{l}{A}$ or $R=\rho\frac{l}{A}$, where l is the length of the wire, A is the area of cross-section, and ρ (rho) is a constant for any one material and is known as the specific resistance of the material.

Now suppose $l=1$ cm. and $A=1$ sq. cm., then by substitution in the above expression ρ is *numerically equal* to R, i.e. *the* **specific resistance** *of a material may be defined as the resistance between opposite faces of a cm. cube of the material.* For example, ρ is the resistance between the faces P and Q

(Fig. 154) to the passage of a current in the direction of the arrow.

Note.—The specific resistance ρ is NOT the resistance of a cubic cm. of the material as the resistance of any such given volume of material may be widely varied by altering its shape. ρ which is usually dependent upon temperature, will therefore be expressed in ohms per cm. cube, e.g. ρ for copper at 18° C. is $1{\cdot}63 \times 10^{-6}$ ohms per cm. cube, or 1·63 microhms per cm. cube 10^{-6} ohm $= \frac{1}{10^6}$ ohm $= 1$ microhm.]

Note.—ρ is **NOT** $1{\cdot}63 \times 10^{-6}$ ohms *per cc.*

If the inch is taken as the unit of length, then ρ will be expressed in ohms per inch cube.

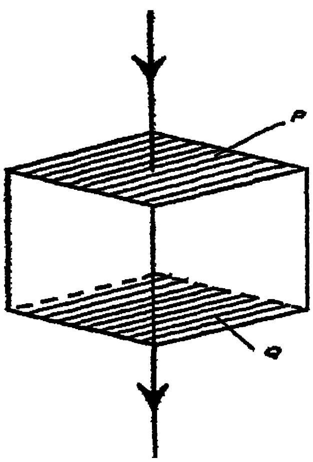


FIG. 154.

Experiment.—To determine the specific resistance of the material of a wire. Obtain a length of wire which should be free from kinks and place it in one of the gaps of a metre bridge or in the fourth arm of a Post Office box. Determine the resistance R of the wire as indicated previously. Next measure the length l of the wire, taking care to exclude from the measurement the parts that are in contact with the terminals of the bridge. The diameter of the wire is then obtained by means of a micrometer screw gauge, and measurements should be made in at least twelve places in two directions at right angles. If d is the mean value of the diameter, and A is the corresponding area of cross-section, then $A = \frac{\pi d^2}{4}$. Great care should be exercised in measuring the diameter, for since d is squared any error introduced in its measurement doubles the error in the value obtained for A.

$$\text{Since } R = \rho \cdot \frac{l}{A}\,.$$

$$\text{Then } \rho = R \cdot \frac{A}{l}\,.^*$$

* As the dimensions of A/l are those of a length, it follows that the unit of specific resistance may be also expressed as an *ohm. cm.*

Experiment. To make a 1-ohm coil.—Take a known length of the wire provided for the purpose of the experiment and determine its resistance by means of the metre bridge. Make sure that the measured length is that of the free wire, and that it does *not* include the ends of the wire which are in contact with the terminals of the bridge. Next calculate the length of wire required to give a resistance of 1 ohm and cut off this length from the wire provided. Wind the wire round a suitable bobbin, taking care, if the wire is uninsulated, that adjacent coils are not in contact. An ordinary lead pencil will serve as a bobbin if nothing more suitable is available.

By means of the Wheatstone bridge measure the resistance of the coil constructed, and so check the accuracy of the work.

Experiment. To determine what length of the wire B must be joined in parallel with one metre of the wire A so that the joint resistance may be one ohm.—Measure off one metre of the wire A and determine its resistance by means of the Wheatstone bridge. Let this be x ohms. If the required resistance of the wire B which is to be connected in parallel with the wire A is y ohms, then $\frac{1}{x}+\frac{1}{y}=1$. Calculate the value of y from this equation.

Next measure the resistance of a known length of the wire B, and from this determine the length required to give a resistance of y ohms. Cut off this length and join it in parallel with the one metre length of the wire A. Check the accuracy of the work by measuring the resistance of the two wires by means of the Wheatstone bridge.

Example.—The diameter of 24 Standard Wire Gauge (S.W.G.) wire is ·022 in. Calculate the resistance of 100 yards of 24 S.W.G. eureka wire if the specific resistance of eureka is 18·9 microhm per inch cube. (1 microhm $=\frac{1}{1000000}$ ohm.)

$$\text{The resistance } \mathrm{R}=\rho\frac{l}{\mathrm{A}} \text{ ohms.}$$

$$\text{Now } l=100 \text{ yards}=3{,}600 \text{ ins.}$$

$$\mathrm{A}=\frac{\pi d^2}{4}=\frac{\pi\times 0\cdot022^2}{4} \text{ sq. ins. where } d=\text{diameter of wire}$$

and $\rho=18\cdot9\times10^{-6}$ ohms per in. cube.

$$\therefore \mathrm{R}=\frac{18\cdot9\times10^{-6}\times3600\times4}{\pi\times0\cdot022^2} \text{ ohms}=\mathbf{179\cdot1 \text{ ohms.}}$$

Example.—The specific resistance of manganin is 41 microhms per cm. cube. What length of manganin wire of S.W.G. 22 is required to give a resistance of 1 ohm? (Diameter of 22 S.W.G. wire $= \cdot 0711$ cm.)

In this example $R = 1.0$ ohm, $\rho = 41.0 \times 10^{-6}$ ohm per cm. cube and $A = \dfrac{\pi \times \cdot 0711^2}{4}$ sq. cm.

$$\therefore l = \frac{RA}{\rho} = \frac{1 \cdot 0 \times \pi \times 0 \cdot 0711^2}{41 \cdot 0 \times 10^{-6} \times 4} \text{ cms.}$$
$$= \mathbf{96 \cdot 85 \text{ cms.}}$$

Resistance Coils and Boxes.—The coils in Post Office or other types of resistance boxes are usually constructed as indicated in Fig. 155. The silk covered wire (w) comprising any coil is wound on a wooden or brass bobbin, B, so that the wire is doubled on itself at the middle of its length. This *non-inductive winding*, as it is termed, is adopted to avoid self-induction effects (see Chap. XIII) at the make and break of the current in the circuit containing the resistance, and to prevent the current which is passing in the coil from creating a magnetic field in its neighbourhood, which would for example directly disturb the indications of a moving needle galvanometer. The coils are insulated carefully with shellac varnish and in high grade apparatus they are protected from the effects of moisture by a coating of paraffin wax.

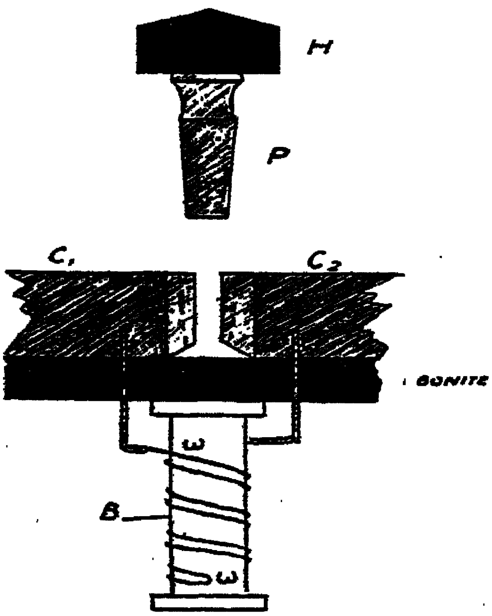


Fig. 155.

The ends of each coil are soldered to brass blocks (C_1, C_2, etc.) fixed to the ebonite cover of the box. Plugs of brass (P) with ebonite handles (H) closely fit into the conical gaps separating the brass blocks, and when any plug is in position the current will flow almost completely through it from the one contacting block to the other. In other words the coil will be *short-circuited* by reason of the fact that the cross-

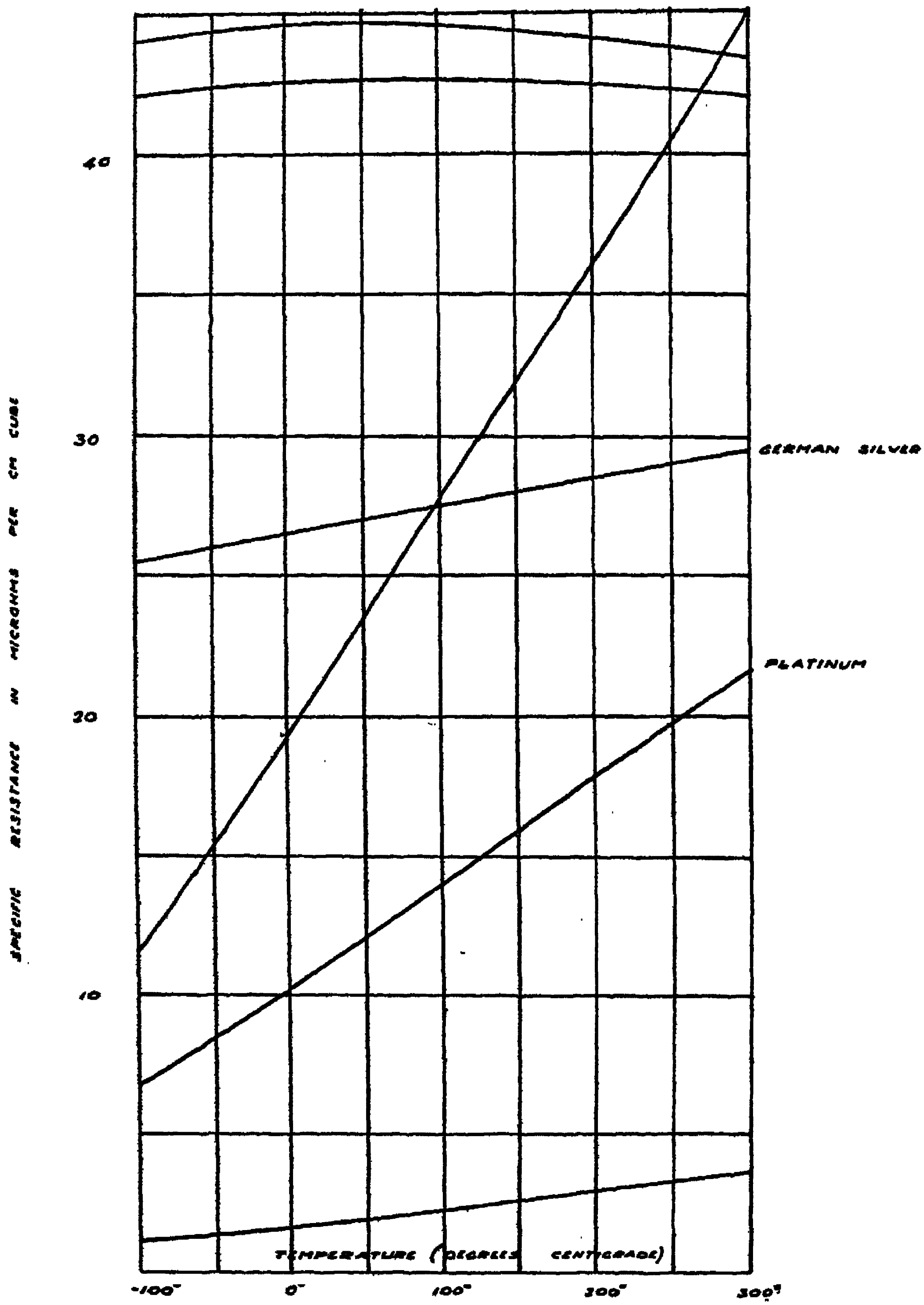
section of the block is very large, and hence its resistance is extremely small. It is obvious that the removal of any plug will insert the corresponding resistance in circuit.

Another form of resistance box which is finding increased favour by reason of recent improvements in design, is that known as the dial type. It consists essentially of a contacting or switch arm which moves in a circle about a centre, and in turn makes electrical contact with a number of metal studs. A series of resistance coils, often identical in value, are connected between the studs. A dial resistance box is generally composed of a number of dial units connected in series.

The material of the wire forming a resistance coil should be such that it changes very slightly with temperature, and remains unaltered with time when its temperature is maintained constant. Alloys, e.g. manganin and German silver, satisfy the former condition and also the latter, provided the wire is carefully annealed by heating to a suitable temperature. Furthermore, alloys have an added advantage over pure metals in possessing a higher specific resistance, so that in constructing a given resistance a smaller length of wire will be required.

The cross-section of the wire to be used for any coil is chosen so that its insulation will not be damaged by the heating of an electric current, unless this exceeds a maximum permissible value. As a general rule the power dissipated in *any coil* of a resistance box should not exceed 0·1 watt. In potentiometer measurements standard resistances are required which will carry large currents, and for this purpose they are specially designed to enable them to be cooled by oil immersion.

EFFECT OF TEMPERATURE ON RESISTANCE.—When a pure metal such as copper, iron or platinum is heated its electrical resistance increases (see Fig. 156). This behaviour may be explained by the fact that, according to the dynamical theory of heat (cf. page 11), the thermal agitation of the atoms of the metal will become greater as the temperature rises, i.e. the oscillations of the atoms about their positions of rest will be more rapid. Consequently the moving electrons will suffer more collisions with the metallic ions, or, in other words, the resistance to their motion will be increased, just as it is harder to progress through a flock of agitated sheep than through a forest of stationary trees. It follows from the



GRAPHS SHOWING THE EFFECT OF TEMPERATURE ON THE RESISTANCE OF METALS

FIG. 156.

above reasoning that as the temperature of a metal is reduced its resistance will decrease also, and it is even found that with some metals such as lead and mercury the resistance becomes negligible at very low temperatures. This property is known as "supra-conductivity," and means that the electrons have almost complete freedom of movement, so that when a current is "induced" (see Chapter XIII) in a closed ring of the metal, kept at these low temperatures, it will continue to circulate for an extremely long period of time.

Over a small range of temperature (say 0° C. to 100° C.) the change in resistance of a large number of metals is proportional to the increase in temperature. Hence if R_t and R_o are respectively the resistances of a conductor at t° C. and 0° C., then $R_t - R_o$ is $\propto t$.

$$\text{It follows that } \frac{R_t - R_o}{R_o} \text{ is } \propto t$$

$$\text{or } \frac{R_t - R_o}{R_o \,.\, t} \textit{ is a constant.}$$

This constant is usually written as α (alpha), and is known as the *temperature coefficient of resistance* over this temperature range. The identity $\dfrac{R_t - R_o}{R_o t} = \alpha$ may also be written as $R_t = R_o\,(1 + \alpha t)$ which expresses the linear relationship between resistance and temperature.

The value of α for a number of metals is approximately $+0{\cdot}004$ per ° C., which means that the resistance of a pure metal increases about 1% for each 2·5° C. rise in temperature.

Experiment.—To measure the temperature coefficient of resistance of a wire.—Wind the wire *non-inductively* (page 214) on a frame of an insulating material, wood is suitable if covered wire is employed, and solder the free ends to thick copper leads passing through a cork which closes the open end of the test-tube container (Fig. 157). Connect this resistance in the "open" arm of a Post Office box or a metre bridge, and with the test tube placed in a beaker containing melting ice, determine the value of the resistance when it has become constant,

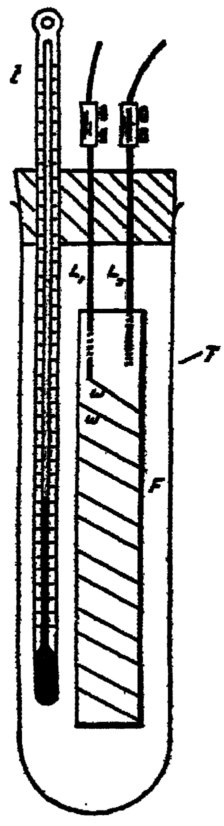


FIG. 157.

i.e. when it has attained the temperature of the melting ice. Let the resistance of the wire at this temperature be denoted by R_o. Next repeat the experiment with the test tube placed in a beaker of water heated in turn to a number of different temperatures between 0° C. and 100° C., the temperatures being observed with a mercury thermometer. Tabulate your results as below and plot a curve showing the relation between resistance and temperature.

Temperature ° C.	Resistance of wire in ohms.

From the curve obtained, deduce the resistance of the wire at 100° C., i.e. R_{100}, and hence calculate the temperature coefficient α from the expression $\alpha = \dfrac{R_{100} - R_o}{R_o \times 100}$

Example.—A platinum thermometer (see below) was connected in one arm of a Post Office box and its resistance at 0° C. and 100° C. was found to be 2·83 and 3·83 ohms respectively. Determine the temperature coefficient of platinum over this range of temperature

$$\text{Here } R_o = 2{\cdot}83\omega \text{ and } R_{100} = 3{\cdot}83\omega.$$

$$\therefore\ \alpha = \frac{R_{100} - R_o}{R_o \times 100} = \frac{3{\cdot}83 - 2{\cdot}83}{2{\cdot}83 \times 100} = \frac{1{\cdot}00}{283}$$

i.e. $\alpha =$ **0·00353 per ° C.**

Resistance Thermometry.—When the temperature coefficient of resistance of a metal has been accurately found, its value can be utilised for the actual experimental determination of temperature. For this purpose the resistance R_o of the conductor at 0° C. must be measured, and if R_t is its resistance at the unknown temperature t° C., then it follows since $R_t = R_o\ (1 + \alpha t)$, that $t = \dfrac{R_t - R_o}{R_o\ .\ \alpha}$.

A suitable metal for use as a resistance thermometer is platinum, as it has a fairly large temperature coefficient and its resistance-temperature relation does not depart so widely from a straight line as in other metals. Furthermore, it is not easily oxidised and consequently can be employed up to 1,000° C., if inserted in a protective porcelain tube. The fine platinum wire (about 0·005 in. diameter) is wound on a mica frame and its free ends are hard-soldered to copper leads. For very accurate work the variable resistance of the leads is eliminated by employing a second pair connected to a very short piece of platinum wire, which explains the presence of the four terminals at the "head" of the *resistance pyrometer* shown in Fig. 158. The *difference* in the resistances of the two platinum wires is now measured.

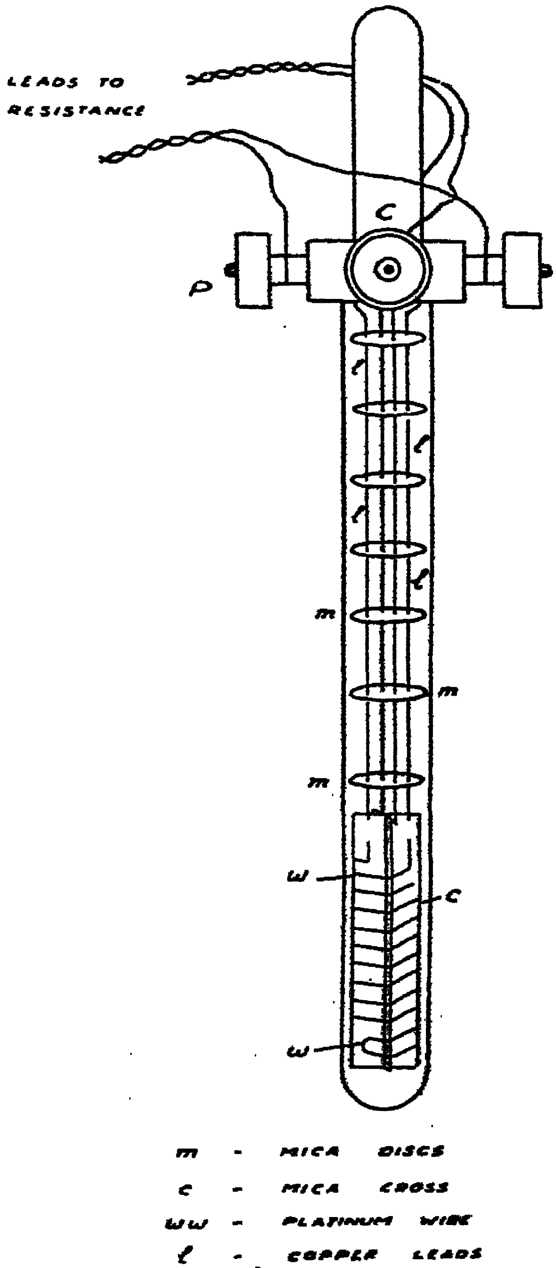


FIG. 158.

RESISTANCE COILS.—The change of resistance of alloys with temperature is much smaller than for pure metals. Thus the resistance of German silver which is an alloy of copper, zinc and nickel increases with temperature at about one-tenth of the rate that the resistance of pure copper does, while the rate of increase for manganin (an alloy of copper, nickel and manganese) is found to be less than $\frac{1}{200}$ of that of copper.

Consequently when it is desired that the resistance of a coil should remain as constant as possible, e.g. in resistance boxes, alloys are invariably used for the winding of the coils.

Experiment.—To determine the resistance of a metal filament lamp when varying values of current pass through it.—A lamp is connected in series with an ammeter, a rheostat and a key. A voltmeter is connected to the terminals of the lamp. Before the circuit is closed, care should be taken that the positive terminals of both instruments are on the positive side of the circuit. When the whole resistance is in, close the key. Enter the ammeter and voltmeter readings if these are fairly high. Next, slowly diminish the resistance, and at various stages during the process, take the readings of the two instruments. As the current is allowed to increase the lamp gradually becomes hotter, and eventually attains white heat. Calculate the resistance for various values of the current and tabulate the results as follows :

Current (amps.).	Potential difference (volts).	Resistance $= \frac{\text{P.D.}}{\text{Current}}$	Amps. × volts =watts.

Plot the resistance against the wattage, which can be regarded as a rough indicator of the temperature. The curve obtained should show that the resistance of tungsten increases with temperature.

Iron is often employed for the filaments of barretters, which are regulating lamps included in an electrical circuit (e.g. in a wireless receiving set) in order to keep the value of the current constant. This effect is *attained* by a suitable choice of the gas, in the lamp, and of the filament resistance, so that the given current heats the wire to about 670° C. At this temp. the increase of res. of iron is very large.

Experiment.—To determine the resistance of a carbon lamp when varying values of current pass through it, proceed as in the previous experiment.

On plotting a resistance-current curve it will be noted that the resistance *decreases* with a rise of temperature.

The temperature coefficient of resistance of carbon is therefore *negative*. The same is true for glass and other so called insulators. The resistances of all electrolytes decrease very rapidly with rise of temperature, which means that the +ve and −ve ions (page 145) can move more easily through the solution. The explanation of the effect, however, is too complicated to consider here.

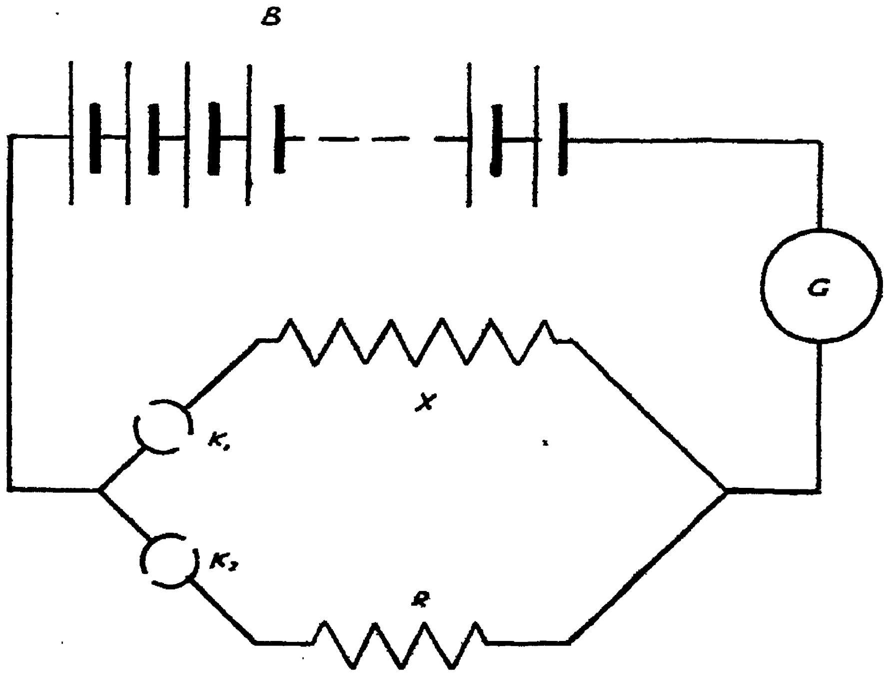


FIG. 159.

MEASUREMENT OF HIGH RESISTANCE.—In the case of the measurement of resistances of the order of a megohm (10^6 ohms) and upwards the ordinary Wheatstone bridge method is unsuitable since the bridge is insensitive under these conditions.

The simplest method which may be employed is a *direct deflection* method, the circuit connections being shown in Fig. 159.

Let X be the unknown resistance and let R be a known high resistance, e.g. a megohm.

K_1 is a key placed in the arm of the circuit containing X, and K_2 is a key in the arm containing R. G is a sensitive galvanometer.

Let E be the electro-motive force of the battery, B its resistance, and let G be the resistance of the galvanometer. Let the current through the circuit be I_1 when the key K_1 only is closed and let δ_1 be the corresponding galvanometer deflection. Then

$$I_1 = \frac{E}{B+G+X} = K\delta_1 \quad . \quad . \quad . \quad . \quad (1)$$

Where K is a constant of the galvanometer.

If I_2 is the current in the circuit when the key K_2 only is closed, and δ_2 is the corresponding galvanometer deflection, then

$$I_2 = \frac{E}{B+G+R} = K\delta_2 \quad . \quad . \quad . \quad . \quad (2)$$

Dividing (1) by (2)

$$\frac{B+G+R}{B+G+X} = \frac{\delta_1}{\delta_2}$$

The value of B is negligible by comparison with X, R and G, and

$$\therefore \frac{G+R}{G+X} = \frac{\delta_1}{\delta_2} \text{ very approximately.}$$

$$\text{Hence } X = \frac{(\delta_2-\delta_1)G+\delta_2 R}{\delta_1}$$

A high resistance which is suitable for a laboratory experiment is obtained by drawing a fairly thick pencil line on a sheet of glass and clamping the glass with terminals so that they overlap the pencil mark. Alternatively a glass tube about 30 cms. long and 1 cm. diam., with upturned ends for the insertion of wire electrodes, may be used if the tube is filled with ordinary distilled water.

THE MEGGER.—The "*Megger*" is a direct-reading instrument for the measurement of insulation resistances. Fig. 160 shows diagrammatically the construction and connections (indicated by dotted lines) of a type of the instrument manufactured by Evershed and Vignoles. The poles at the left-hand end of the permanent magnet system form the magnetic field of the measuring instrument or **ohmmeter.** The ohmmeter consists of three coils (C, P and B) rigidly connected so that they move together with the pointer *n*. The current coil C is connected in series with a resistance *r*, the unknown

resistance X and the applied e.m.f. which is supplied by the generator G. X is actually inserted between the line (L) and earth (E) terminals of the instrument, and r is a resistance to protect the current coil if these terminals should be accidentally short-circuited. The pressure coil P is connected in series with a compensating coil B, and a high resistance R across the terminals of the generator. The windings of the pressure and current coils are such that the coils tend to rotate the moving

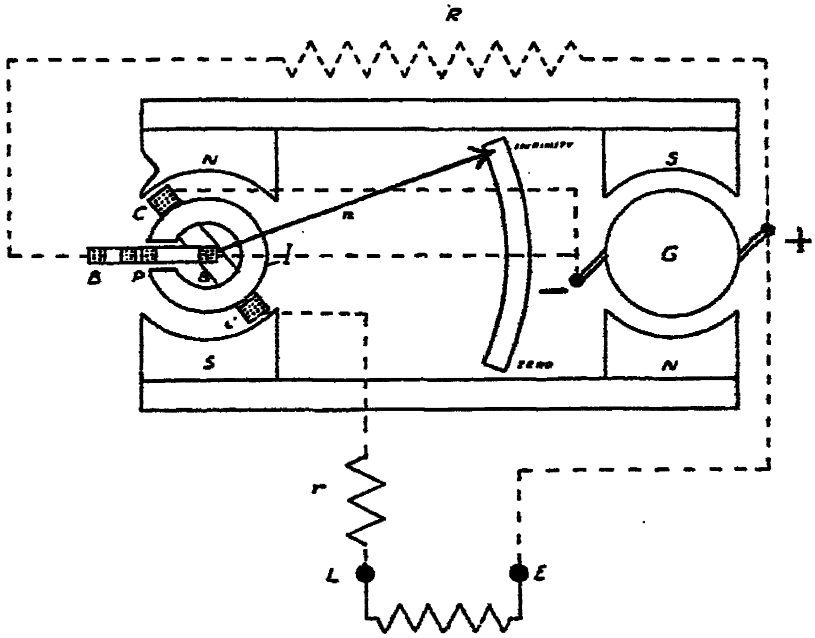


FIG. 160.

system in opposite directions when a current passes through them. The system will thus move to a position of equilibrium where the turning moments exerted by the coils are equal in magnitude.

The coil B is wound in opposition to P, and its purpose is to minimise the effect of stray magnetic fields, and also to render the scale divisions of the instrument more uniform. This uniformity is also improved by the shaping of the left hand upper pole as indicated in the diagram. The generator G which is incorporated in the instrument is hand-driven and supplies an e.m.f. of the order of 500 volts. "Meggers" are designed to cover a wide range of maximum values from 10 megohms to 10,000 megohms.

RESISTANCE OF A CELL.—The theory of the experiment described below becomes clear by considering a circuit in which a cell B is connected in series with a key K, and a resistance box R. When the circuit is closed the current I that flows through it is the same in all parts, and the electro-motive force of the cell can be regarded as being used for two purposes, viz. (1) to drive the current through the cell itself, and (2) to drive it through the resistance in the box. When no current is flowing the potential difference between the plates of the cell gives the value of the electro-motive force of the cell (page 162). When a current flows through the circuit the potential difference between the plates drops in value and is equal to the part of the electro-motive force which is used to drive the current through the resistance in the box. The remaining part of the electro-motive force is used to drive the current through the resistance of the cell itself.

Experiment.—To determine the resistance of a cell using a voltmeter.—Connect a cell B to a resistance box R through a key K. Also connect a voltmeter V to the terminals of the cell. Let E be the voltmeter reading when no current is passing through the cell. Close the circuit and insert a resistance of R ohms in it. If B ohms is the resistance of the cell, V the voltmeter reading, and I the current flowing through the circuit, then if Ohm's Law is applied to the whole circuit,

$$I = \frac{E}{B+R},$$

and if Ohm's Law is applied to the part of the circuit outside the cell,

$$I = \frac{V}{R}$$

$$\therefore \frac{E}{B+R} = \frac{V}{R}$$

$$\text{or } V(B+R) = ER$$

$$\therefore VB = ER - VR = (E-V)R$$

$$\text{and } B = \frac{(E-V)R}{V}$$

Begin by making the resistance R small and gradually increase it. Take a series of readings and tabulate the results as follows:—

R (ohms)	E (volts)	V (volts)	$B=\left(\frac{E-V}{V}\right)R$ (ohms)

As R increases, the value of the current flowing through the circuit diminishes. It is found that the resistance of a cell becomes greater as the current passing through it is decreased.

In the case of a cell like the Leclanché which polarises rapidly, the value of E cannot be assumed to remain constant throughout the experiment. Its value should be observed and recorded for each determination made.

Comparison of Electro-motive Forces of Cells.—The electro-motive forces of cells can be compared approximately by connecting the different cells in turn to a voltmeter, and reading the values of the electro-motive forces directly on the instrument. The objection to this method lies in the fact that there is a small potential drop in the cell itself, whose value depends upon the current in the circuit and upon the resistance of the cell. This potential drop is not included in the voltmeter reading and consequently the method is not suitable when exact values are required. It is clear that the higher the resistance of the voltmeter in comparison with that of the cell, the greater is the accuracy of the result obtained. The e.m.f. of a Weston Cadmium Cell (page 168) cannot be obtained by this method owing to its high internal resistance.

Sum and Difference Method.—This method is due to Wiedemann, and consists in comparing the strengths of the currents derived from the two cells (1) when they

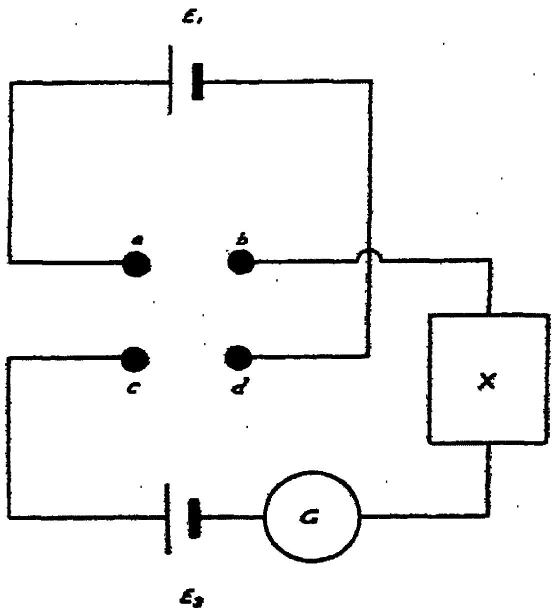


Fig. 161.

are connected so as to act in conjunction, and (2) when they are connected so as to act in opposition.

The scheme of connections is shown in Fig. 161. E_1 and E_2 are two cells whose electro-motive forces E_1 and E_2 respectively are to be compared. X is a resistance box, *abcd* is a quadrant key and G is a tangent galvanometer. When $a—b$ and $c—d$ are connected the cells work in conjunction. When $a—c$ and $b—d$ are connected they oppose each other. Let R be the resistance inserted in the box X, G the resistance of the galvanometer, and B the total resistance of the two cells. If I_1 and θ_1 are respectively the current and deflection when the cells act in conjunction, and I_2 and θ_2 the corresponding quantities when the cells are in opposition, then if K is the constant of the galvanometer,

$$I_1 = \frac{E_1+E_2}{B+G+R} = K \tan \theta_1 \qquad . \quad . \quad (1)$$

and

$$I_2 = \frac{E_1-E_2}{B+G+R} = K \tan \theta_2 \qquad . \quad . \quad (2)$$

Dividing (1) by (2)

$$\frac{E_1+E_2}{E_1-E_2} = \frac{\tan \theta_1}{\tan \theta_2}$$

Hence *

$$\frac{E_1+E_2+E_1-E_2}{E_1+E_2-E_1+E_2} = \frac{\tan \theta_1+\tan \theta_2}{\tan \theta_1-\tan \theta_2}$$

$$\text{or } \frac{E_1}{E_2} = \frac{\tan \theta_1+\tan \theta_2}{\tan \theta_1-\tan \theta_2}$$

If a mirror galvanometer is used in place of a tangent galvanometer, and θ_1 and θ_2 respectively are the deflections obtained, then

$$\frac{E_1}{E_2} = \frac{\theta_1+\theta_2}{\theta_1-\theta_2}$$

---

* If $\frac{a}{b} = \frac{c}{d}$, each $= \frac{a+c}{b+d}$.

Put $\frac{a}{b} = \frac{c}{d} = k$. Then $a = bk$, $c = dk$.

$$\therefore \frac{a+c}{b+d} = \frac{bk+dk}{b+d} = \frac{(b+d)\,k}{b+d} = k$$

$$\text{and } k = \frac{a}{b} = \frac{c}{d}$$

The galvanometer employed in the experiment should have a low resistance and a high sensitivity. Care should also be taken to adjust the resistance R in the box at the beginning of the experiment, so that suitable deflections are obtained for both arrangements of the cells.

The Potentiometer Method.—In the Sum and Difference Method described above it is assumed that the resistances of the cells remain constant. This need not necessarily be the

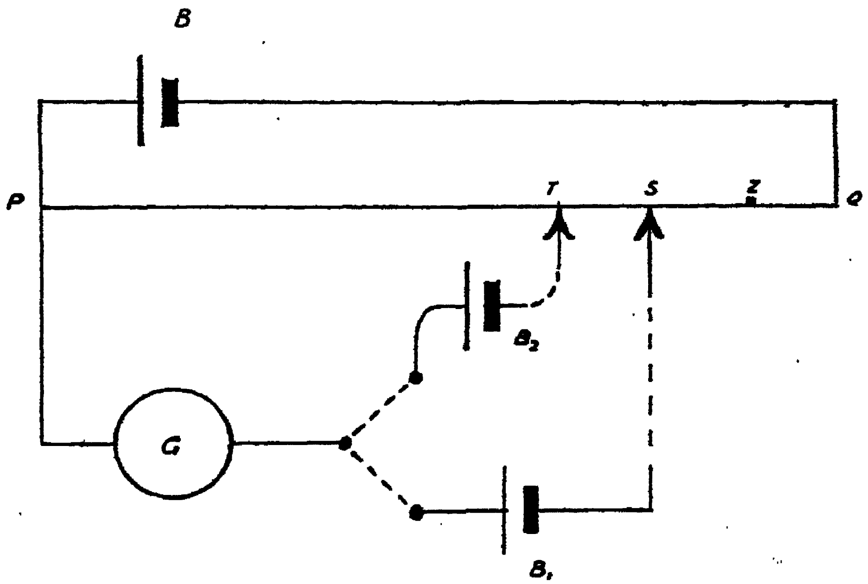


FIG. 162.

case. Also the effects of polarisation which may be taking place in the cells are ignored. In the potentiometer method of comparing electro-motive forces the theory does not involve the resistances of the cells. It is also a ***null method.*** No current passes through the test cell and consequently no polarisation can occur in it. The potentiometer method is thus superior to the sum and difference method.

The principle of the potentiometer is as follows: A battery B (Fig. 162) whose electro-motive force E is greater than that of any cell which is to be tested, is connected to the terminals of a stretched uniform wire, PQ. In the case of such a wire the resistance is proportional to the length. Hence, since the current flowing through the wire is the same in all parts, it follows that the potential drop along it is proportional to

the length taken. Thus, if any point Z is taken in the wire

$$\frac{\text{Potential drop between P and Z}}{\text{Potential drop between P and Q}} = \frac{\text{Length PZ}}{\text{Length PQ}}$$

If one of the cells under test, B_1, is connected as shown, and no current passes through the galvanometer when contact is made at the point S on the wire, then the electro-motive force of the cell is equal to the potential drop between the points P and S on the wire. Let E_1 be the electro-motive force of the cell B_1 and E that of the cell B. If $PS=l_1$ and $PQ=L$, then

$$\frac{E_1}{E} = \frac{l_1}{L} \quad . \quad . \quad . \quad . \quad (1)$$

If the cell B_1 is replaced by the cell B_2 of electro-motive force E_2 and balance is obtained at T, where $PT=l_2$, then

$$\frac{E_2}{E} = \frac{l_2}{} \quad (2)$$

$$\text{From (1) and (2)} \; \frac{E_1}{E_2} = \frac{l_1}{l_2} \; .$$

In testing a cell a bad contact on the wire might prevent any current flowing through the galvanometer. It is consequently advisable in making measurements to test the reliability of the result obtained by making contacts on opposite sides of a point which gives no deflection. The deflections thus obtained should be in opposite directions.

Experiment.—To obtain the recovery curve for a Leclanché cell.—The potentiometer can be used to determine the rate of recovery of a rapidly polarising cell like that of the Leclanché. The cell is first "shorted" for about three minutes and the balance point on the potentiometer wire quickly determined. The balance point is again determined after a minute's interval, and this procedure is continued for some time, the results being tabulated as shown.

Time.	Length of wire (in cms.).
0 min.	
1 ,,	
2 ,,	
3 ,,	

Since the length of wire is proportional to the electro-motive force a curve indicating the rate of recovery of the cell is obtained, by plotting the lengths against time. The curve obtained is of the form shown in Fig. 163. The flat part of the curve, of course, gives the value of the maximum electro-motive force of the cell.

Measurement of Energy.—Instruments which are used for the measurement of energy must not indicate merely the rate at which energy is supplied, i.e. the power, but must also take into consideration the period of time during which power is being supplied.

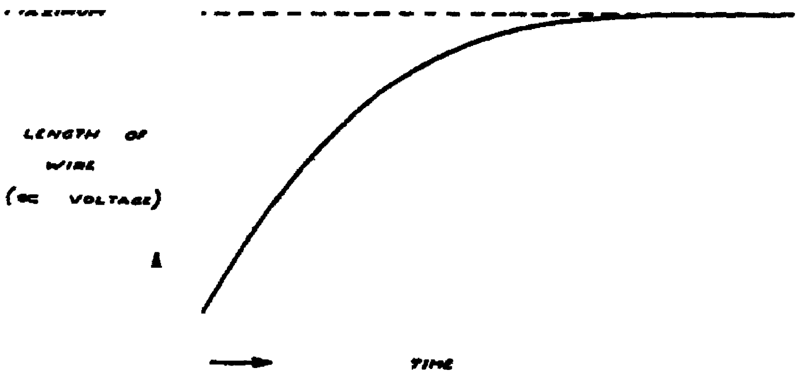


Fig. 163.

The three general types of these instruments are (1) *Electrolytic* meters, (2) *Motor* meters and (3) *Clock* meters.

Electrolytic meters are essentially D.C. instruments, but may be employed on A.C. if used in conjunction with a rectifier. The second and third types of meters may be used for A.C. or D.C. measurements. Supply meters employed on D.C. circuits are either watt-hour meters or amp.-hour meters. The latter type are really only quantity meters, but since the voltage supply is nowadays invariably constant then the readings of these instruments have only to be multiplied by the supply voltage to obtain watt-hours.

The action of electrolytic meters depends upon the application of Faraday's Laws of Electrolysis (page 146) which can be expressed as $w=zQ$, where w is the mass (in gms.) of substance deposited or decomposed by a quantity of electricity Q (coulombs), and z is the electro-chemical equivalent of the substance. If I is constant for t secs., $Q=It$ coulombs when I is in amps., and the meter is therefore an amp.-hour meter.

In practice electrolytic meters are difficult to read accurately owing to the small amount of chemical decomposition permissible, and to the difficulty of resetting the meter. Furthermore, there is a loss of energy in the meter itself, owing to the back e.m.f. of polarisation set up when the current is flowing. The Bastian meter (Fig. 164) consists of two concentric nickel electrodes E_1 and E_2 immersed in a solution of sodium hydroxide. The passage of the current decomposes the water of the solution into oxygen and hydrogen which are liberated, and consequently the liquid level falls. If the tube is uniform in cross-section, the change in level will be directly proportional to the quantity of electricity passing through the meter. Evaporation from the surface of the solution in the tube is minimised by using a layer of paraffin oil.

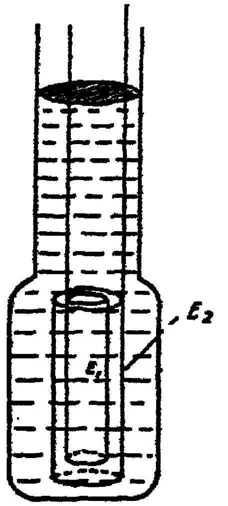


FIG. 164.

The Ferranti mercury meter (Fig. 165) is one of the oldest and best known examples of the "quantity" type of motor meter. A light amalgamated copper disc (D) is fixed to a

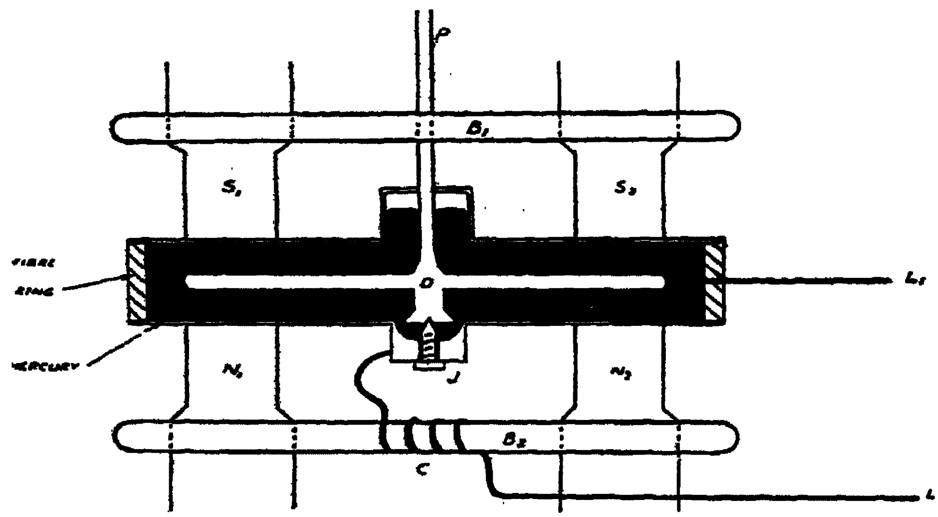


FIG. 165.

spindle (P), which drives the counting mechanism through a suitable system of gears. The disc rotates on a jewelled bearing (J) in a bath of mercury. The mercury is contained in a brass box which has an internal insulating lining of fibre. L is

the lead carrying the current via the mercury into the disc at its periphery, and thence the current flows radially to the centre and is finally conveyed away via the jewelled bearing and the lead, L_2. S_1N_1 and S_2N_2 are the poles of two C-shaped permanent magnets, and the interaction between their magnetic fields and the current in the disc causes the latter to rotate (cf. the moving-coil galvanometer, page 182). Actually the speed of rotation of the disc will be controlled by the eddy currents (page 268) induced in it, due to the cutting of the magnetic field during its rotation.

It can be shown that the uniform speed (N revolutions per sec. say) of the disc is directly proportional to the current (I), so that in a given time (t secs.) the total number of revolutions ($N \times t$) made will be proportional to the quantity ($I \times t$) of electricity passed in that time. In practice it is found that the friction experienced by the disc in the mercury increases with the speed of rotation. In order to compensate for this error two steel bars B_1 and B_2 are placed across the magnet poles, and the meter current is passed through a coil C wound about the lower bar, so that an increase in current has the effect of increasing the driving torque without affecting the braking torque.

The clock type of meter can only be briefly mentioned here. It consists essentially of a pendulum which is electrically driven by clockwork, so that the bob is acted upon by gravity and by a field of force due to the meter current passing through a solenoid. Actually two pendulums are connected so that the difference between their periods of oscillation is proportional to the power in the circuit, and this difference is recorded by a suitable mechanism.

QUESTIONS.

1. Explain in detail, with a diagram, the method of measuring resistance by means of a Wheatstone Bridge. For approximately what range of resistance measurement is this method most suitable? (U.L.C.I., B, 1935.)

2. Describe, giving a connection diagram, the principle of action of the simple potentiometer.

Explain how a potentiometer may be used to compare the E.M.F.'s of two cells. Give a connection diagram. (U.E.I., S2, 1935.)

3. Describe the construction and principle of action of some form of ohmmeter. Give a connection diagram. (U.E.I., S2, 1933.)

4. Explain, with a sketch, the construction and action of any modern ampere-hour meter. (N.C.T.E.C., 1933.)

5. Discuss the limitations of the ammeter-voltmeter method for measuring resistance. Why is the method particularly unsuitable for the measurement of high resistance?

6. Deduce the relationship between the resistances in the arms of a balanced Wheatstone Bridge, i.e. when no current flows through the galvanometer. How would you use the Bridge to measure the resistance of a coil of wire?

7. Define Specific Resistance.

The specific resistance of copper is 0·0000018 ohm. per cm. cube. Find the resistance of a copper wire whose length is 100 cm. and the area of whose cross section is 0·20 sq. cm.

8. State how the resistance of a wire depends upon its length and area of cross-section. A piece of wire 80 cm. long and 1 mm. in diameter has a resistance of 3·5 ohms. What will be the resistance of a wire of the same material 1·25 metres long and 0·5 mm. in diameter?

9. Define the "electro-motive force" of a cell.

A cell is connected to a voltmeter and its e.m.f. is found to be 1·5 volts. If a coil of 4 ohms resistance is connected in parallel with the voltmeter the reading of the instrument falls to one volt. Calculate the resistance of the cell.

10. The e.m.f. of a battery (i.e. the difference of potential between the poles on open circuit) is 30 volts. When a long length of thin wire is joined across the battery, a current of 2·5 amps. is produced, and the potential difference between the poles of the battery falls to 20 volts.

Find the internal resistance of the battery and the resistance of the wire. What will be the current if the length of the wire is halved? (C. & G., 1928.)

11. What length of German silver wire of diameter 0·5 mm. must be connected in parallel with a wire of 2 ohms resistance in order that the joint resistance may be 1 ohm? (Specific resistance of German silver is 27×10^{-6} ohm. per cm. cube.)

12. What is meant by the statement that *the temperature coefficient of resistance of a metal is* 0·004 *per deg. C*? How would you find the value of this coefficient for platinum if you were given 20 cms. of thin platinum wire?

CHAPTER XIII

INDUCED CURRENTS

ELECTRO-MAGNETIC INDUCTION.—The phenomenon dealt with in this chapter is of extreme importance as the conversion of mechanical into electrical energy depends upon it, and it is furthermore the basic principle of many electrical devices of the present day, e.g. the telephone.

After Oersted's discovery that an electric current in a wire (page 68) gives rise to a surrounding magnetic field, it was a natural consequence that experimenters began to seek for the converse effect, i.e. the *induction* or creation of a current in a conductor by setting up an independent magnetic field in its neighbourhood.

About 1831 two scientists, Faraday in England and Joseph Henry in America, although working independently, discovered the effect almost simultaneously and one of Faraday's simple experiments may now be repeated.

Experiment.—Connect the terminals of a coil or solenoid S, consisting of about 200 turns of insulated wire, to a sensitive galvanometer (Figs. 166 (*a*) and (*b*)). The connecting leads from S should be made sufficiently long to avoid any direct inductive influence upon G.

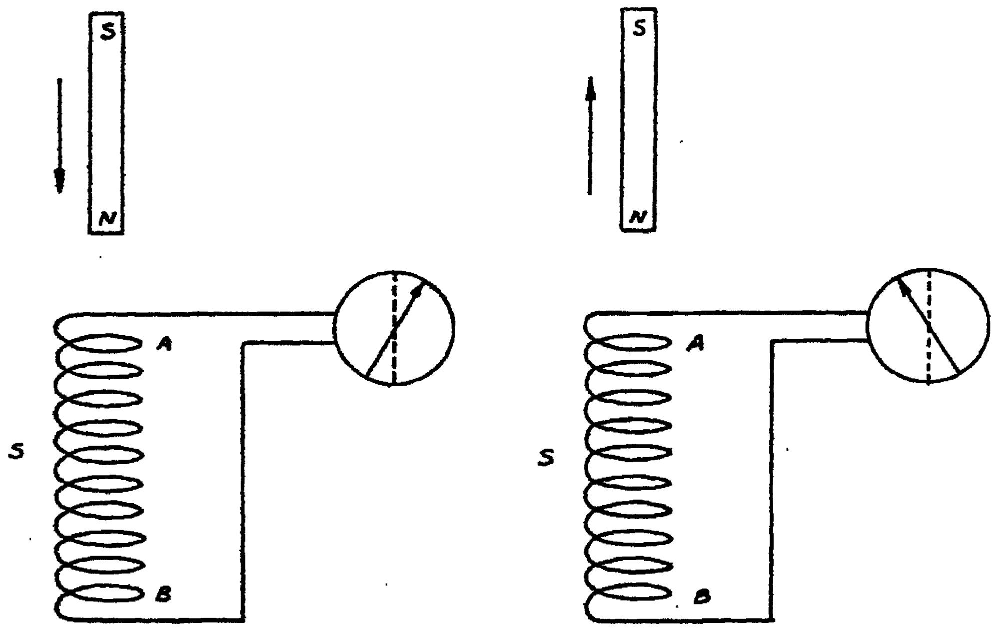
Plunge the north pole of a bar-magnet into one end of the solenoid and observe the *direction* of the galvanometer deflection (Fig. 166 (*a*)). Withdraw the north pole and note that a deflection is again produced, but in the opposite direction (Fig. 166 (*b*)).

Repeat the experiment with the south pole of the magnet and observe that the deflections obtained are in the directions opposite to those observed when the north pole was used, e.g. the direction of the deflection in Fig. 166 (*a*) will be that resulting from the *withdrawal* of the *south pole.*

It should be carefully observed that a deflection is only produced when the magnet is in motion and ceases when the

latter is stationary. To show that it is really only the *relative motion* that matters, keep the magnet stationary and move the coil, when the same effects as above will be noticed.

Summarising, the results of the above experiment show that (1) When a magnet and a *closed* circuit move *relatively* to one another a current is induced in the circuit, and (2) The direction of the induced current is dependent upon the direction of the movement and also upon the polarity of the end of the magnet nearest the coil.



(*a*) FIG. 166. (*b*)

Now in the above experiment the circuit containing the coil has been closed, but it can be shown that if the galvanometer is replaced by a very sensitive form of electroscope, called a quadrant electrometer, then the latter will show deflections of a similar nature to those of the galvanometer, when the magnet and coil are moved relatively to one another. In this case, however, the coil circuit is *open* and hence it may be said that the *relative movement of the magnet and the coil induces an* **E.M.F.** *in the coil*, which will cause a displacement of electrons so that there will be a heaping up at one free end of the coil and a deficiency at the other end. It is evident that when the ends of the coil are joined to form a closed circuit a momentary or *transient* current will be produced in the circuit.

The next question to be considered is the exact relationship between the direction of the induced e.m.f. (or current), and the polarity of the "inducing" pole of the magnet. This problem may be best investigated from the point of view of energy, and for this purpose it must be remembered that a current-carrying solenoid behaves like a bar-magnet as regards its magnetic effects (page 71).

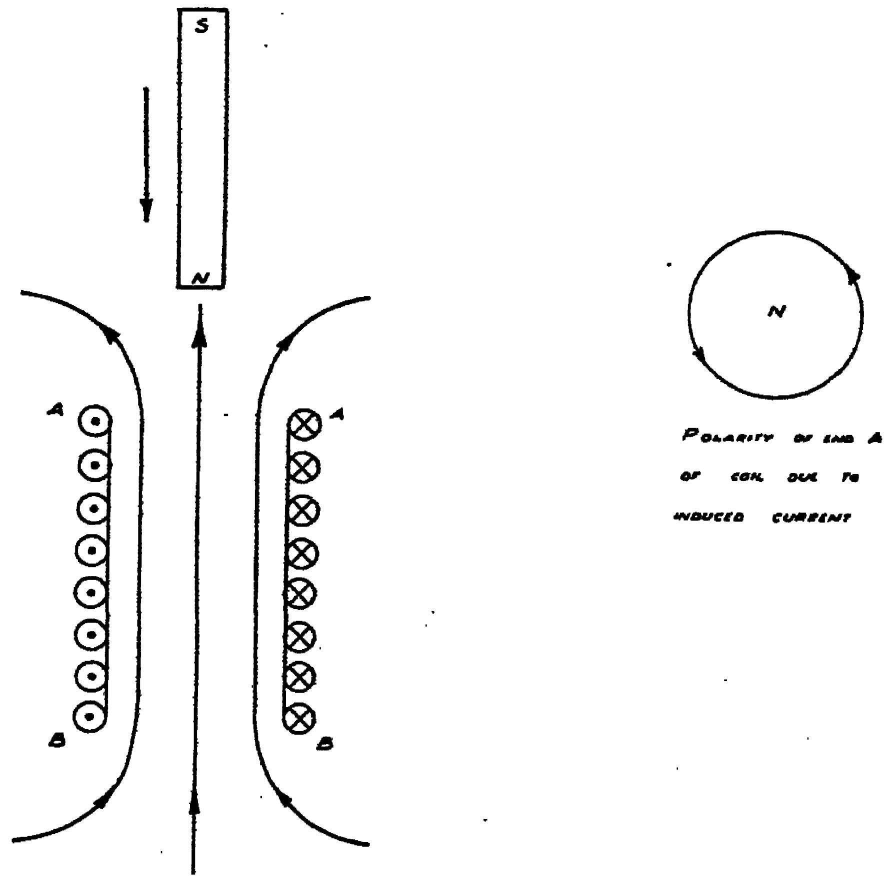


FIG. 167.

Now the production of an induced current (or e.m.f.) in the closed circuit must be the result of an expenditure of energy, and this can only occur if work is done in bringing, say, the north pole of the magnet towards the coil. This condition implies that the north pole must experience a repulsive force, which means that the direction of the current induced in the coil must be such as to create a north polarity at the end nearest to the north "inducing" pole. (Fig. 167.)

Similar reasoning applies to the *withdrawal* of the north pole from the coil. In this case work must be performed

against an *attractive* force, i.e. the direction of the induced current must be such as to create south polarity at the end nearest the "inducing" pole.

In both the above cases it is therefore evident that the current induced in the circuit flows in such a direction as to create a magnetic field, which exerts a force opposing the motion of the inducing pole.

The above deductions should now be verified by the following experiment:

Experiment.—Connect up the solenoid S, a galvanometer G, a battery B and a rheostat R to the two-way key K, as indicated

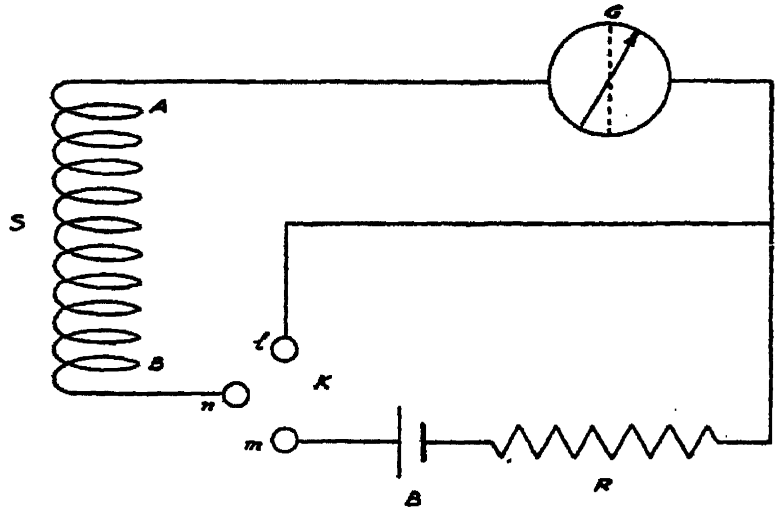


FIG. 168.

in Fig. 168. By means of the two-way key, *n* may be connected to either *l* or *m*.

Connect *n* and *m* and adjust R to obtain a suitable deflection in a *noted* direction.

With the current flowing obtain the polarity of the end face A of the solenoid by placing a small compass needle near it. Let it exhibit north polarity, say.

Now change the key connection from *m* to *l*, so that *n* and *l* are joined, and approach the A face of the solenoid with the north pole of a magnet. According to the above deductions this movement should induce a current in the solenoid such that the end A exhibits north polarity, i.e. the galvanometer deflection should be in the same direction as when the cell was joined in circuit with the galvanometer. Verify that this is correct and in a similar manner investigate the case when the magnet is withdrawn from the coil.

Lenz's Law.—The observations made during the above experiments should now be examined as to whether they obey the following general law formulated by a Russian scientist, Lenz (1804-1865): "*Whenever the number of lines of magnetic force in a circuit are changing there is an induced e.m.f. in the circuit, and the direction of this e.m.f. is such as to tend to oppose the motion or change producing it.*"

In the experiments performed the circuits were closed, hence the direction of the induced e.m.f. is inferred from the observed direction of the induced current.

Magnitude of the induced e.m.f.

Experiment.—Connect the solenoid S in series with the galvanometer G, as in Fig. 167, and observe how the value of the galvanometer deflection, i.e. how the magnitude of the induced e.m.f. (and current), depends upon the following factors:

(1) The *rate* at which the magnet is moved relative to the coil.

(2) The pole strength of the magnet (i.e. use two similar magnets singly and together).

(3) The number of turns in the coil.

From the observations of the above experiment verify the truth of the following law of electro-magnetic induction: "Whenever the number of lines of magnetic force, i.e. magnetic flux (page 120), within a circuit is changing there is an induced e.m.f. set up in that circuit. **The magnitude of the induced e.m.f. is directly proportional to the rate of change of magnetic flux.**"

It should be noted that in the above experiment the circuit is closed and it is the value of the induced *current* which is directly observed, but it is obvious that by Ohm's Law this is strictly proportional to the magnitude of the induced e.m.f., if the resistance of the circuit is kept constant.

Consider the case of a coil consisting of a single turn of wire, and suppose that φ_1 and φ_2 represent respectively the number of magnetic lines of force (i.e. flux) passing through the coil at the beginning and at the end of a period of t secs.

Then the magnitude of the induced e.m.f. (in c.g.s.) is given by

$$E = \text{Rate of change of flux}$$

$$= \frac{\text{Change of flux}}{\text{Time in seconds}} = \frac{(\varphi_2 - \varphi_1)}{t} \text{ c.g.s.}$$

Now the practical unit of e.m.f. is the volt and

$$1 \text{ volt}=10^8 \text{ c.g.s.}$$

$$\text{Hence } E = \frac{(\varphi_2 - \varphi_1)}{t \times 10^8} \text{ volts}$$

If there are N turns of wire in the coil

$$\text{then } E = N \times \frac{(\varphi_2 - \varphi_1)}{t \times 10^8} \text{ volts}$$

The product of the number of turns of wire and the flux is known as the *number* of *linkages*. Hence $N \times (\varphi_2 - \varphi_1)$ represents the change in linkages.

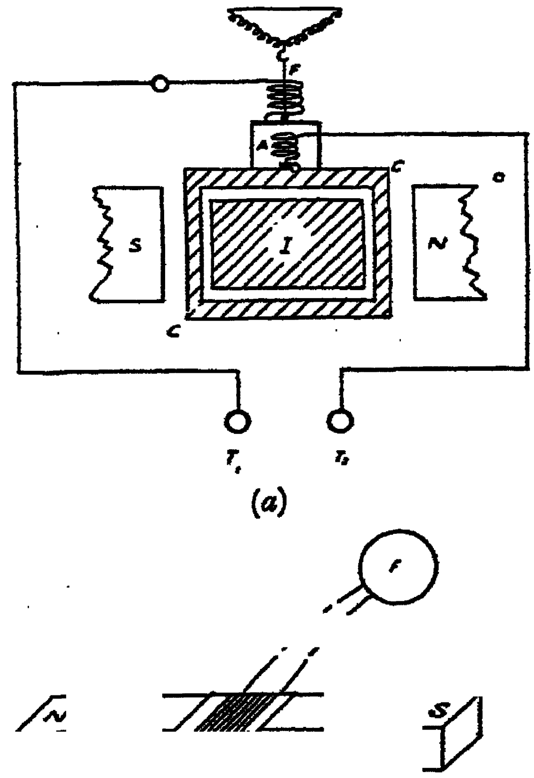
Measurement of Magnetic Flux.—If the magnetic flux through a coil *changes* by an amount φ^1 in a very small interval of time t^1 secs., then the induced e.m.f. is $\varphi^1/t^1 \times 10^{-8}$ volts, and the instantaneous value of the current flowing in the coil if included in a closed circuit of total resistance R, is given by $i^1 = \frac{1}{R} \cdot \frac{\varphi^1}{t^1} \times 10^{-8}$ amps. (by Ohm's Law). The total quantity of electricity flowing through the circuit in this very small interval of time t^1 will be equal to $q_1 = i^1 t^1 = \frac{\varphi^1}{R} \times 10^{-8}$ coulombs. It therefore follows that if Φ is the *total* change of flux then the *total quantity* of electricity passing in the circuit is $Q = q_1 + q_2 + \cdots = \Phi/R \times 10^{-8}$ coulombs, which is *independent* of the *time* taken to perform the change. Hence to measure the magnetic flux passing through a circuit it is necessary to find the quantity of electricity produced by, say, reducing that flux to zero, and the type of instrument commonly used for this purpose is the **ballistic galvanometer.** The chief characteristics of this galvanometer are small damping and a moving system possessing a large moment of inertia, so that the discharge of electricity passes through the instrument before the system shows any appreciable movement. It can be shown that the total quantity (Q) of electricity passing is proportional to the first throw (d_1) produced on the galvanometer scale by the discharge.

Consider a single turn of wire (*abcd*) set with its plane perpendicular to a uniform field of strength H c.g.s. Then the flux passing through the coil in this position is $\varphi_1 = A \times H$, where A is the area enclosed by the coil. Suppose the coil is now rotated through 180°, then the flux passing

through the coil is now $\varphi_2 = -A.H$ since, although the field has not changed its direction, the coil has been reversed which produces an identical result. Hence the change in flux is $\varphi_1 - \varphi_2 = AH - (-AH) = 2AH$, and will be proportional to the galvanometer throw d_1 produced by the quantity of electricity passing in the circuit. It follows that by using the same *search* coil and galvanometer in different magnetic fields, their strengths will be directly proportional to the respective throws, i.e. $H \propto d$.

Experiment.—Use an earth inductor (i.e. a coil containing a large number of turns of insulated wire wound on a non-magnetic frame of large area) in conjunction with a ballistic galvanometer, to compare the values of the horizontal and vertical components of the earth's magnetic field. Hence deduce a value for the angle of dip.

The Fluxmeter is a form of ballistic galvanometer having a large moment of inertia, and the construction of the instrument is shown in Fig. 169 (*a*). S and N are the poles of a powerful permanent horseshoe magnet, C the suspended flux-meter coil, I a soft iron core, F a silk fibre suspension attached at its upper end to a shockproof flat spiral spring, and AA two flat spiral silver strips to lead the current respectively in and out of the coil and which together exert practically no torsional control. For the purpose of measuring the strength of magnetic fields a search coil is connected in series with the instrument. In the case of very strong fields the coil will require only to have a small sectional area and few turns.


(*a*)
(*b*)
FIG. 169.

Experiment.—To find the pole strength of a given bar-magnet.

Obtain a cardboard former C (Fig. 169 (*b*)) which closely fits around the bar-magnet NS, and wind over it say 30 turns

of No. 32 S.W.G. insulated copper wire to occupy a length of 1 or 2 cms. Place the coil over the centre of the magnet, connect it to the fluxmeter terminals and note the stationary reading θ_1 of the pointer. Holding the coil firmly in position completely remove the bar-magnet, and observe the maximum indication θ_2 of the fluxmeter. If this reading is " off " the scale, reduce the number of turns in the search coil, or alternatively if $\theta=(\theta_2-\theta_1)$ is too small, then its value should be increased by augmenting the number of turns.

Let m be the pole strength of the magnet, a the cross-sectional area of the magnet, n the number of turns in the search coil and k the fluxmeter constant (i.e. the number of maxwell-turns per scale division deflection).

Now 4π lines of force emanate from a unit pole, therefore the flux passing through the search coil initially$=4\pi m$, and hence the original number of flux linkages$=4\pi mn$ maxwell-turns. It follows that $4\pi mn=k\theta$ or

$$m=\frac{k\theta}{4\pi n}\text{. unit poles}$$

Example.—A coil is wound with 1,000 turns of wire and has an area of 500 sq. cms. It is held with its plane vertical and at right angles to the magnetic meridian at a place where the horizontal component of the earth's field is 0·18 gauss. If the coil is turned through 90° about an axis in the plane of the coil in $\frac{1}{30}$ sec., find the electro-motive force generated in it in volts.

The horizontal component of the earth's field is 0·18 gauss, so that the total number of lines cutting the coil is

$$\begin{aligned}&=\text{Field Strength}\times\text{Area of Coil (sq. cms.)}\\&=0{\cdot}18\times500\\&=90\end{aligned}$$

∴ Rate of change of the number of lines threading the coil

$$-\frac{90}{1/30}=2700.$$

$$E=\begin{matrix}\text{Rate of change of the number of}\\\text{lines threading the coil}\end{matrix}\times\begin{matrix}\text{Number of turns of}\\\text{wire in the coil}\end{matrix}$$

$$\begin{aligned}&=(2700\times1000)\text{ c.g.s. units}\\&=27\times10^5\text{ c.g.s. units}\\&=\frac{27\times10^5}{10^8}\text{ volts}\\&={\cdot}027\text{ volt.}\end{aligned}$$

Mutual Induction.—Since the magnetic properties of a current-carrying solenoid resemble those of a bar-magnet (page 71), it is evident that the phenomenon of electromagnetic induction observed in the previous experiments could also have been produced, if the bar-magnet had been replaced by such a solenoid. For the purpose of verifying this conclusion it is suggested that the following experiment be performed.

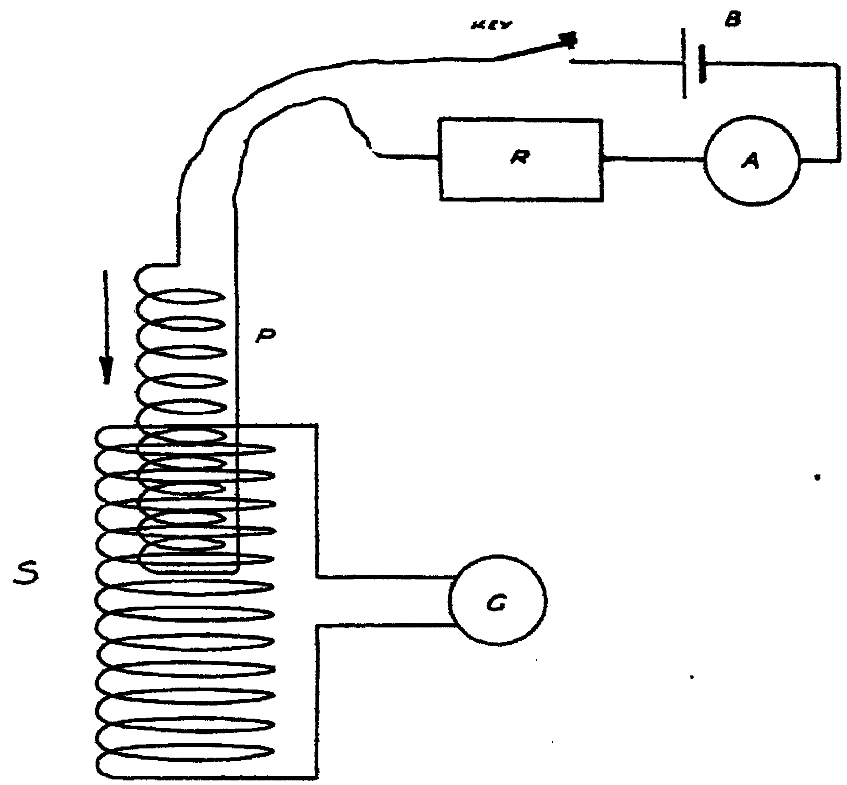


Fig. 170.

Experiment.—Take two solenoids, P and S, such that the former fits inside the latter (Fig. 170). Connect the coil P in series with a key, a cell B, a resistance box R, and an ammeter A. A sensitive galvanometer G is joined in circuit with the coil S. The connections to both coils should be by means of fairly long leads.

The coil P carrying the *inducing* current is known as the *primary* coil, while the coil S in which the e.m.f. (and current) is *induced* is called the *secondary* coil.

Employing the current-carrying primary coil as the bar-magnet repeat the procedure of the experiments on pages 233

and 235, and hence verify the laws of electro-magnetic induction both as regards magnitude and direction. In regard to the latter, the polarity of the lower end of the coil P will have to be found by means of a compass needle. Furthermore the strength of the "inducing-action" of the primary coil will be directly proportional to the current flowing in the coil and may be altered by varying the resistance R, the corresponding value of the current being read on the ammeter A.

There remains a third and very important method of producing an e.m.f. by induction. The mode of its production depends upon the fact that the magnetic flux through the secondary coil of the arrangement in the previous experiment is varied, not by moving the primary coil, but by suddenly changing the value of the current passing through it. This change may be effectively brought about by merely closing or opening the key K (Fig. 170) in the primary circuit, so that the corresponding rise and decay of the current is very rapid.

Experiment.—Place the coil P inside the coil S as in Fig. 170. Close the primary circuit and note the direction of the momentary deflection of the galvanometer. Open the key K and observe that the galvanometer is deflected in the opposite direction.

Any change in the magnitude of the primary current will be found to cause a deflection of the galvanometer. This fact is made evident by closing the key K and suddenly increasing or diminishing the resistance R, when deflections in opposite directions will be obtained.

Determine, as in previous experiments, the directions in which the inducing and induced currents flow in the primary and secondary circuits respectively, and verify the following:

(1) *On making* or *increasing* the current in the primary circuit, the induced current is in the *opposite* direction to the inducing current, and

(2) *On breaking* or *decreasing* the primary current, the induced and inducing currents are in the *same* direction.

Figs. 171 (*a*) and (*b*) show the directions of the currents in the coils and also the corresponding magnetic fields, that due to the induced current being indicated in dotted lines.

It should be noted that these results are in agreement with Lenz's Law, which will also be obeyed if the experiment is repeated with the direction of the *primary* current *reversed.*

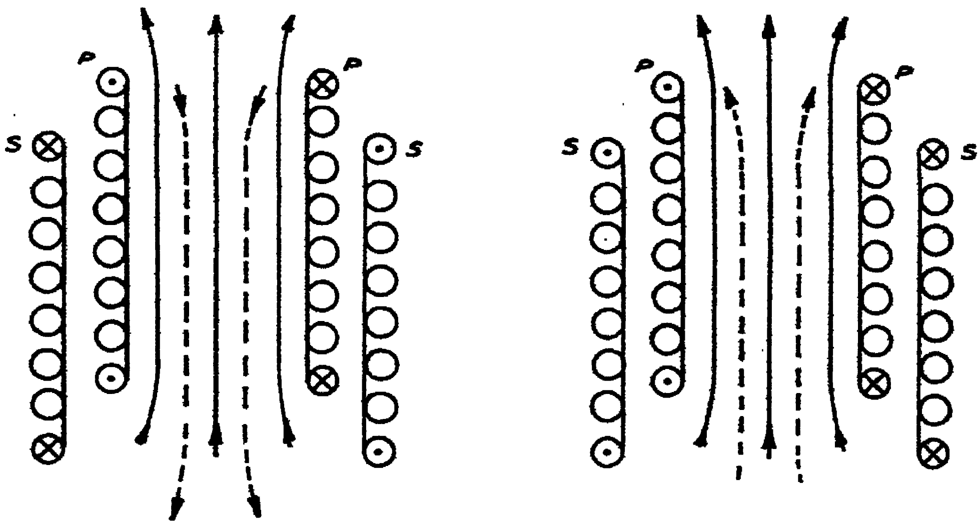
These results may be briefly and conveniently expressed as :

A **D**irect induced e.m.f. (or current) is produced by a **D**ecrease of flux, and

An **In**verse induced e.m.f. (or current) is produced by an **In**crease of flux.

Experiment.—Using the apparatus as set up in Fig. 170, investigate how the magnitude of the induced e.m.f. is affected by,

(1) *The relative positions of the coils P and S.* i.e. show that the galvanometer deflection on making the same current in



(*a*) FIG. 171. (*b*)

the primary coil, is increased if this coil is inserted further into the secondary coil, and

(2) *The presence of a soft iron rod inside the coils.* i.e. show that in this case also the induced e.m.f. is greatly increased, owing to the high permeability (page 96) of the iron causing a considerable increase in the magnetic flux through the primary coil.

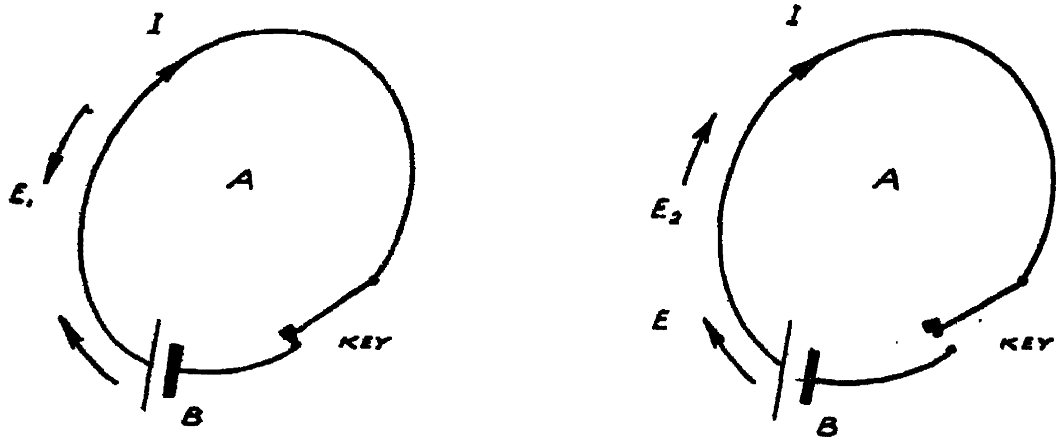
It is obvious that the same effects as those observed above are obtained if S is used as the primary and P as the secondary coil, although their magnitude would differ if the resistances of P and S are different. Consequently since this inductive effect between two circuits is mutual it is referred to as **Mutual Induction.**

Self-Induction.—Just as a change of current in a closed circuit A (Fig. 172) reacts on neighbouring circuits, so does it react in a similar manner upon itself. For when a current in

such a coil is started (or increased) the magnetic field created sets up an e.m.f. in the coil (by Lenz's Law), which is in a direction *opposite* to that of the applied e.m.f. The effect of this back e.m.f. of self-induction, as it is termed, is to prevent an instantaneous rise of current in the circuit to its final value as determined by Ohm's Law.

The arrow E_1 (Fig. 172 (*a*)) indicates the direction of the back e.m.f. when the current I is growing, and its magnitude must obviously be always less than the applied e.m.f. E for the current to increase in the circuit at all.

When the circuit is opened, or the current I is decreased, the induced e.m.f. E_2 (Fig. 172 (*b*)) tends to maintain the



(*a*) Closing Circuit. FIG. 172. (*b*) Opening Circuit.

previous value of the current, i.e. it acts in the same direction as the applied e.m.f. E. In this case, if the circuit is *broken*, the magnitude of this "after" e.m.f. as it is termed, will depend upon the rapidity of the operation, and for a highly "inductive" circuit will lead to sparking at the contacts of the switch. Special precautions have therefore to be adopted to prevent the rapid burning away of these contacts, as illustrated in the case of the induction coil (page 247).

The effect of self-induction in a circuit may be conveniently demonstrated by the following experiment.

Experiment.—In Fig. 173 C consists of a coil containing three or four hundred turns of insulated wire wound upon an iron core, composed of a bundle of soft iron wires. L is a 6 volt electric lamp, B is a 2 volt accumulator and K is a switch.

When the switch is closed and a steady current is flowing the lamp filament may just glow, but on suddenly breaking

the circuit (by opening K) it will momentarily flash up brilliantly as a result of the high after e.m.f. of self-induction.

Now the property of a body which tends to keep it at rest or in motion, as the case may be, is known as its *inertia.* It obviously depends directly upon the mass of the body since it is easier to set say a marble in motion, than it would be a cannon-ball. A particular device in which this property is utilised is the fly-wheel, which is the means of storing up the work done by an engine, so that if the output of the latter fluctuates slightly, the machinery which is driven directly from the *massive* fly-wheel is practically unaffected. It is evident that a considerable amount of energy has to be expended in setting the fly-wheel in motion, but when the driving engine is stopped, the fly-wheel will maintain its motion for a long time on account of its inertia. If means are adopted for bringing the fly-wheel to rest quickly its stored-up energy will appear in another form, e.g. that of heat.

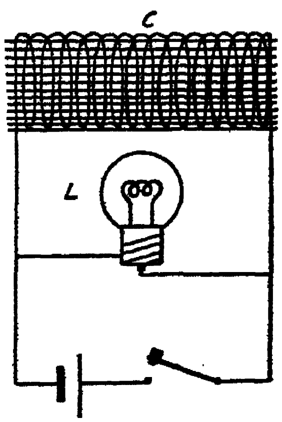


FIG. 173.

Now on comparison, the *self-induction* of an electrical circuit is seen to behave very similarly to the *inertia* of a mechanical system, for in creating a current in a circuit energy has to be expended in overcoming the back e.m.f. of self-induction. On removing the applied e.m.f. (cf. engine) from the circuit, this energy reappears as the "after" e.m.f. which tends to maintain the established current. Again if the circuit is actually broken, this energy is made apparent in the form of a spark at the contacts of the switch. The energy given to the electrical circuit is used in creating its magnetic field, whose lines of force are concentric circles surrounding the conductor (page 68) and these extend further outwards as the current increases. When the circuit is broken these lines of force collapse again into the conductor, and in so doing return their energy to the circuit which is made evident by the "after" e.m.f.

MUTUAL AND SELF-INDUCTION. UNITS.—It has already been seen that if one coil A is in the neighbourhood of another coil B and the current in A is altered, the change in the magnetic field around A creates an e.m.f. in B. Further, by

Lenz's Law the direction of the induced e.m.f. is such that it tends to prevent the change producing it.

If there is a unit rate of change of the current in A the induced e.m.f. in B is called the *coefficient of mutual induction* or *mutual inductance* of the two coils. It is usually denoted by M.

$$\text{Thus Coefficient of Mutual Induction (M)} = \frac{\text{E.M.F. induced in the Secondary Coil}}{\text{Rate of change of the current in the Primary Coil.}}$$

The practical unit of mutual inductance is the **henry**, hence it follows that

$$1 \text{ henry} = \frac{1 \text{ volt}}{1 \text{ ampere per second}}$$
$$= \frac{10^8 \text{ c.g.s. units of e.m.f.}}{10^{-1} \text{ c.g.s. units of current per second}}$$
$$= 10^9 \text{ c.g.s. units of inductance}$$

The coefficient of mutual induction of two coils, measured in henries, is the e.m.f. in volts which is induced in one coil when the current in the other varies at the rate of one ampere per second.

Similarly *the coefficient of self-induction or the self-inductance of a coil is the e.m.f. in volts induced in the coil when the current through it varies at the rate of one ampere per second.* It is measured in *henries* and is usually denoted by L.

The precise calculation of the inductance of a given circuit is in general a difficult matter, but tables are available to enable approximate values to be rapidly calculated, for example, in the case of cylindrical coils. The coils used in wireless circuits have very small inductances so that they are usually expressed in *micro-henries* (1 micro-henry $=10^{-6}$ henry). As an example the inductance of a cylindrical coil with 10 turns per cm., a length of 8 cms. and a diameter of 5 cms. is 154·2 micro-henries. The inductance of a coil of identical size but having 5 turns/cm. would be approximately $\frac{5^2}{10^2} \times 154{\cdot}2 = 38{\cdot}6$ micro-henries, since for closely wound coils the inductance is proportional to the square of the number of turns.

If the various conductors forming a circuit are so disposed that their separate magnetic fields tend to oppose one another so that the resultant magnetic field for the whole circuit is zero, the circuit is said to be *non-inductive* (see also page 214).

In making measurements with a Wheatstone Bridge arrangement (Chapter XII) it will now be evident that if the galvanometer key is closed *before* the battery key a momentary

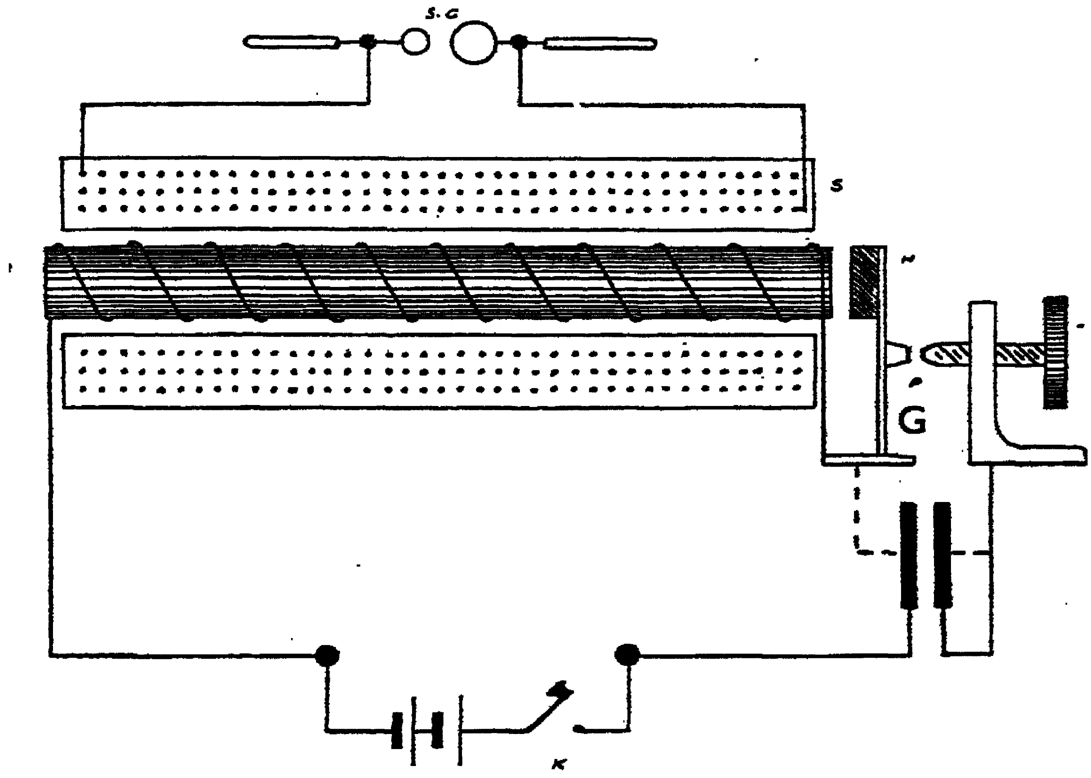


FIG. 174.

deflection of the galvanometer may be obtained, which is due solely to the differences of the inductances in the various arms. This difficulty may be overcome by closing the battery key first. Alternatively, as is generally the practice to-day, the resistance coils are wound non-inductively, i.e. they are wound back on themselves (Fig. 155, page 214), so that the magnetic fields due to the two "halves" of any one coil neutralise one another.

THE RUHMKORFF INDUCTION COIL.—The induction coil (Fig. 174) is a device for obtaining very high voltages at the terminals of a secondary coil when comparatively low voltages are applied to the primary coil. In its present form it was

devised by Ruhmkorff, a manufacturer of physical apparatus, in Paris, and was first exhibited in 1851. The primary coil (Fig. 174) consists of a few turns of fairly thick insulated wire wound round an iron core. The secondary coil S, which is carefully insulated from the primary, may consist of many thousands of turns of fine wire which is encased in paraffin wax to ensure perfect insulation.

When a current from the battery B passes through the primary coil the iron core becomes magnetised and attracts the piece of soft iron H, which is carried on the spring G. When H approaches the iron core the contact at the platinum point D is opened and the primary circuit is broken. The iron loses its magnetism in consequence, and the spring G carries H back to D so that the primary circuit is again closed. The process is then repeated and is recurrent. The frequency of the intermittent currents which pass through the primary in this manner clearly depends upon the stiffness of the spring.

At each make of the current in the primary circuit an e.m.f. is induced in the secondary coil in one direction, and at each break an e.m.f. is induced in it in the opposite direction. Now the magnitude of the induced e.m.f. depends on the rate at which the flux is changing, and owing to the large self-induction of the primary coil the *growth* of current is only slow. Hence the induced e.m.f. at the make is very small by comparison with that at the break, and in practice, therefore, the potential difference between the terminals of the secondary coil is almost uni-directional.

As previously indicated (page 244) the effect of self-induction at the break of the current in the primary causes a spark discharge at the contact point, which in time would be destroyed. By joining a condenser C in parallel with the gap at D this destructive action is diminished, and, furthermore, the insertion of this condenser helps to make the secondary discharge more uni-directional. The explanation of the manner in which the condenser functions is difficult and complicated.

It follows from the principle of the conservation of energy that the higher the induced e.m.f. in the secondary the smaller will be the corresponding currents. In order to improve the efficiency of the coil the iron core is composed of a number of parallel iron wires bound closely together, but suitably

insulated from one another. This procedure is adopted for if a *solid* cylinder of soft iron was employed as a core, quite large currents would be induced in it by the variation of the primary current, and these "eddy-currents" as they are termed (page 268) will cause a heating of the core and consequent loss of energy.

The terminals of the secondary coil are usually connected to two metal rods, provided with ebonite handles, so that the distance of the "spark-gap" (S.G. in Fig. 174) between the ends of the rods is adjustable. The performance of an induction coil is expressed by the length of the maximum air-gap across which it can maintain a spark discharge. For

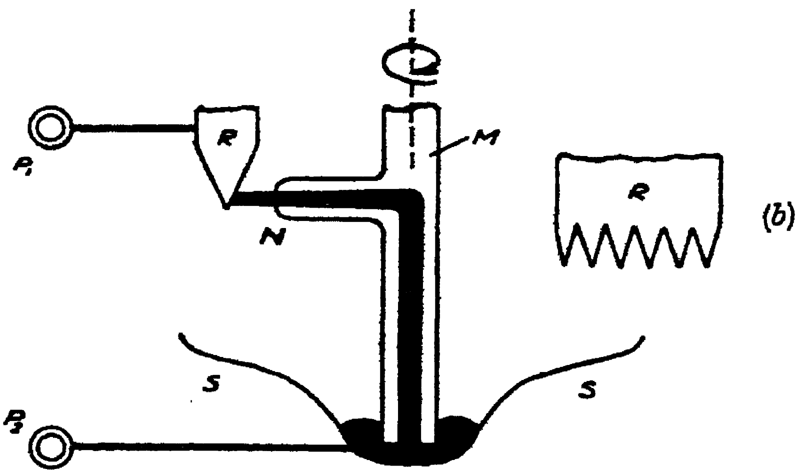


FIG. 175 (*a*).

example, a "one-inch coil" would mean that a maximum P.D. of approximately 30,000 volts (see page 61) can be developed between the secondary terminals.

Induction coils have a variety of uses. They are employed in producing X-rays and in the generation of wireless-waves, also in connection with research work on the structure of the atom. In these applications large coils are needed to provide up to 300,000 volts or more, and in consequence the frequency of the make and break requires to be approximately 70 to 100 per sec. The hammer make and break is unsuitable for these frequencies and amongst others the mercury jet interrupter is employed.

The *mercury jet interrupter* (Fig. 175 (*a*)) consists of a hollow vertical shaft M dipping at its lower end into an iron vessel S containing mercury, which is connected via a battery to one terminal of the primary coil. The shaft is coupled to a

motor and on rotation a stream of mercury issues from the nozzle N, and impinges on a metal ring R which is connected to the other terminal of the primary coil. This metal ring has a serrated lower edge as indicated in the smaller diagram Fig. 175 (*b*), so that the primary circuit will be broken each time the jet passes between these serrations. P_1 and P_2 are terminals.

Transformers.—The advantage of using high voltages for economy of transmission of electrical energy has been already indicated. The use of such voltages, however, will demand apparatus to "step-up" and "step-down" the voltage at the transmission and consuming ends

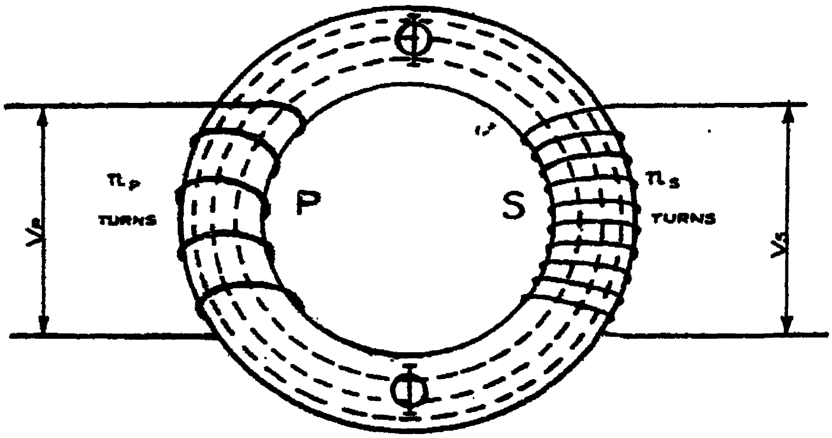


FIG. 176.

respectively, of the transmission line. If A.C. (page 263) is employed both in the generation and transmission this "voltage change" may be effected easily by means of *static* transformers.

The transformer is really an induction coil in which an alternating current replaces the interrupted current through the primary. The simple ring type of transformer, which was first devised by Faraday, is shown in Fig. 176, and consists of a primary (P) and a secondary (S) coil wound round an iron core. If an alternating current is passed through P, an alternating flux is set up in the iron core, which gives rise to an alternating e.m.f. in S (and hence an alternating current if the circuit is closed).

Now assuming that there is no magnetic leakage in the circuit, the same flux φ is linked with both primary and secondary coils, and hence the rate of change of flux is the

same for both coils, i.e. the e.m.f. induced *per turn* of S is equal to the applied e.m.f. *per turn* of P.

Hence if V_P and V_S are the maximum applied and the maximum induced e.m.f.s respectively, it follows from the above that

$$\frac{V_P}{n_P} = \frac{V_S}{n_S} \text{ or } \frac{V_P}{V_S} = \frac{n_P}{n_S}$$

Stated in words it means that

$$\frac{\textit{e.m.f. in secondary coil}}{\textit{e.m.f. in primary coil}} = \frac{\textit{number of turns in secondary coil}}{\textit{number of turns in primary coil}}$$

and this approximate rule is also applicable to the case of the Ruhmkorff coil.

It is evident that there can be two types of transformers according as n_P is less or greater than n_S and they are respectively known as "step-up" and "step-down" transformers.

(1) *Step-up transformers.*—Alternating current at a low voltage is passed through the primary coil and is transformed *up* so as to be transmitted at high pressure.

(2) *Step-down transformers.*—Alternating currents at high pressure are transformed *down* to currents at a low pressure for use in lamps, etc.

Low pressure (or step-down) transformers are an essential part of electric welding machines (page 200) where currents of the order of 1,000 amps. are necessary, the transformation voltage ratio being of the order of 200 to 1. Again in the case of induction furnaces the induced currents may attain a value of 5,000 or 6,000 amps. In these furnaces the secondary circuit consists of a ring-shaped metal tube containing the metal to be melted, which is not therefore brought into contact with contaminating flames.

If the energy lost in a transformer circuit be ignored it can be said that

Output from secondary circuit=Input from primary circuit,

$$\text{i.e. } V_S \times I_S = V_P \times I_P$$

where I_S and I_P are the currents in the secondary and primary circuits respectively.

Further, it has been shown that $\dfrac{V_P}{V_S} = \dfrac{n_P}{n_S}$

$$\text{Hence } \frac{I_S}{I_P} = \frac{n_P}{n_S}$$

The main *energy losses in transformers* are as follows :

(1) Heating losses due to the resistance of the windings and frequently referred to as I^2R losses (or *copper* losses).

(2) Hysteresis losses in the iron core. These losses are kept at a minimum by a careful selection of the iron employed.

(3) Eddy-current losses (cf. page 268). These losses are reduced by forming the core of thin sheets of iron, which are carefully insulated by shellac, etc., from one another.

The hysteresis and eddy-current losses are usually grouped together as iron losses, and for a given transformer they are practically constant at all loads.

The energy losses in a well-designed transformer for high voltages are less than 2%, i.e. the efficiency of the apparatus is between 98% and 99%. In general for *all* types of transformer the efficiency is well over 90%, so that they are more efficient than resistances for reducing the voltage to be applied to a given circuit.

It should be noted that if the secondary circuit is open and a transformer is connected across the A.C. supply, the primary winding owing to its small resistance would appear to short-circuit the mains. Actually, however, only a small current passes in the primary because the e.m.f. of self-induction is almost equal and opposite to that of the applied e.m.f. (cf. choking coil, page 267). When the secondary circuit is closed a current flows in it which sets up a flux opposing the main flux. In consequence the back e.m.f. self-induced in the primary decreases, and more current flows in that circuit. It is evident therefore that the current flowing in the primary circuit is dependent upon the demand made on the secondary circuit.

A CONDUCTOR MOVING IN A MAGNETIC FIELD.

Experiment.—Connect the ends of a conductor, e.g. a rod of brass to the terminals of a sensitive galvanometer. Next, pass the rod rapidly downwards between the poles of a horse-shoe magnet, or preferably between the poles of an electro-magnet. The galvanometer will be deflected.

This result is to be expected as in the early part of the chapter it was seen that an e.m.f. was induced in a conductor (actually a coil was used) when it was moved relative to a magnetic field.

Next move the rod rapidly upwards. The galvanometer will again be deflected, but in the opposite direction.

The experiment shows that when a conductor cuts the lines of force in a magnetic field the mechanical work that is done in conveying the rod through the field is converted into electrical energy, which manifests itself as an induced e.m.f.

Faraday showed the same effect by rotating a copper disc between the poles of a horseshoe magnet (Fig. 177). The brush X which is in contact with the rim of the wheel is connected to the terminal A, and the axle of the wheel is connected to the terminal B. If these terminals are connected

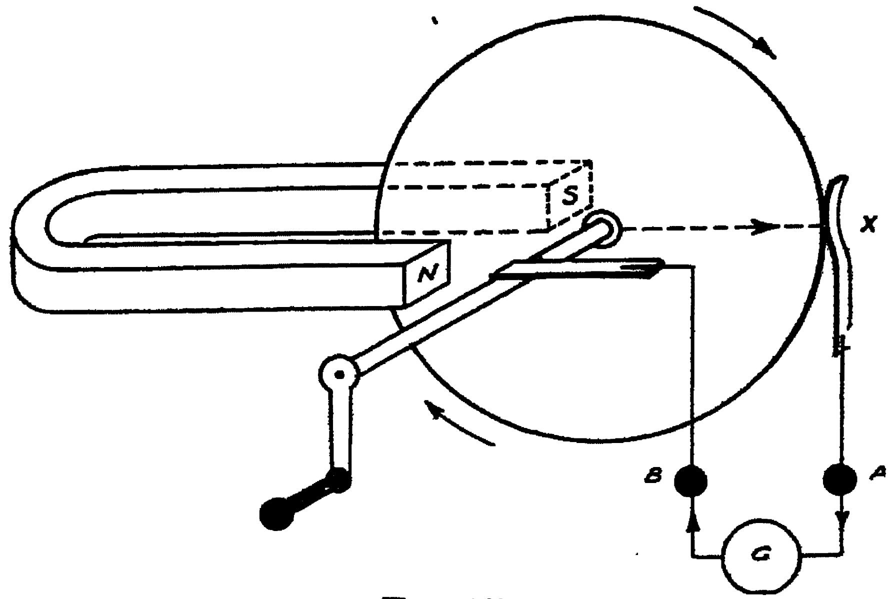


FIG. 177.

to a galvanometer and the wheel is rotated, a deflection is obtained whose direction is determined by the direction of the rotation. When the wheel is rotated in one direction the current flows from axle to rim. When the rotation is reversed the current flows in the opposite direction. In this case mechanical work is done in causing the disc to cut the lines of force of the magnet, and this work is converted into electrical energy.

This conversion of mechanical work into electrical energy illustrates the principle of the *dynamo* (from the Greek word meaning power). In the *motor*, the converse process takes place, viz. electrical energy is converted into mechanical work.

THE MAGNETO.—The internal combustion engine depends for its action on the ignition of a mixture of petrol vapour

and air in the cylinder of the engine, a result which is most conveniently achieved by means of an electric spark. A high voltage (over 7,000 volts) is required for a spark to pass across the small air-gap (approximately $\frac{1}{20}$ cm.) between the platinum

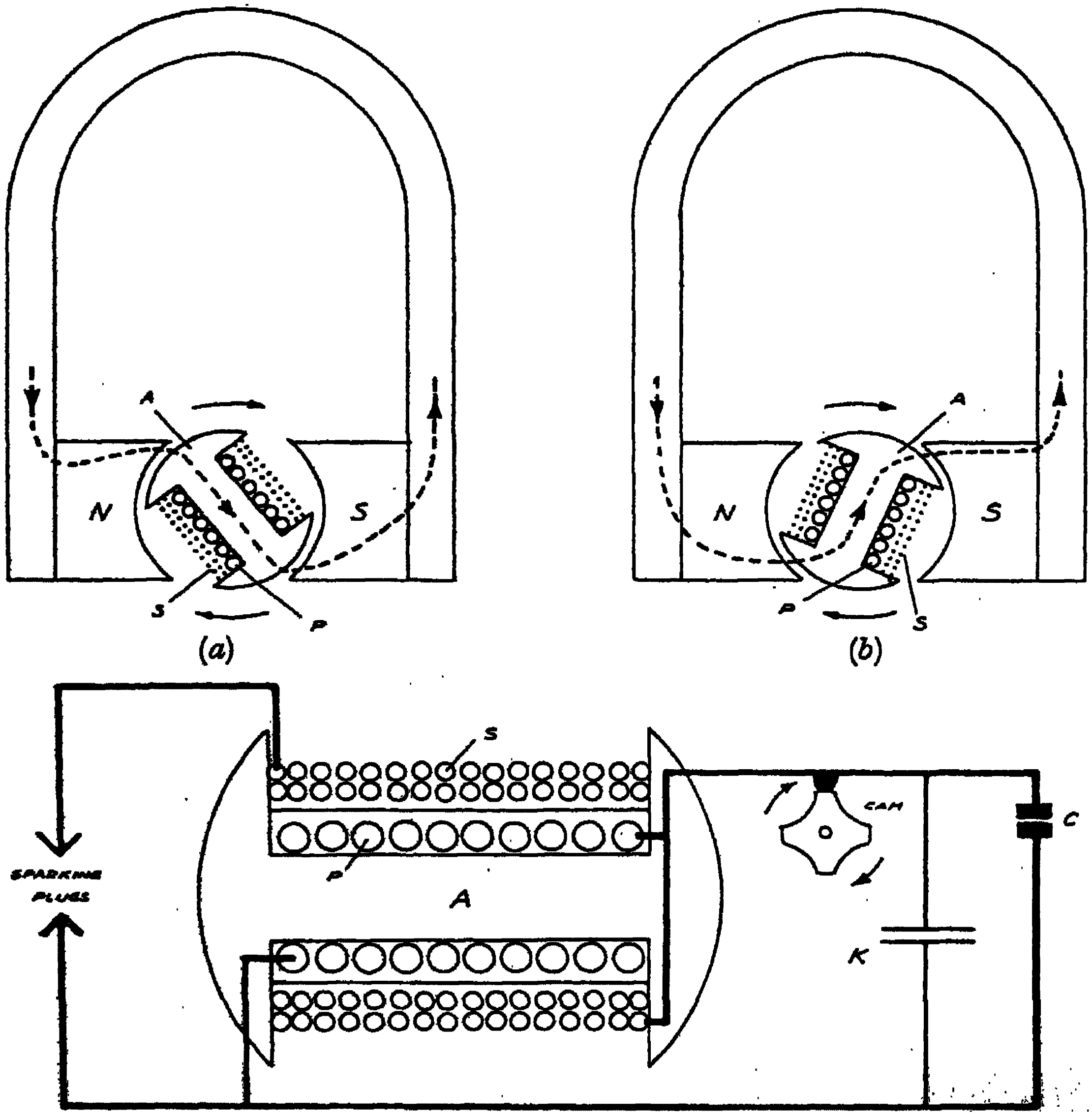


FIG. 178 (c).

points of the sparking plug, and the first device used for this purpose was the induction coil. The drawbacks to this arrangement were the necessity for "housing" a battery of accumulators for supplying the primary current, and the possibility of a sudden failure of the battery, unless particular care is devoted to the condition of the cells. Modern batteries

are now so reliable that induction coils are used in nearly all cars.

The necessity for accumulators is avoided by the use of a magneto, which is virtually a combination of an induction coil and a dynamo. Primary (P) and secondary (S) coils are wound upon a soft iron armature (A) (Fig. 178 (*c*)), which is rotated between the poles of a permanent magnet, by means of the engine. The platinum contacts C are operated by means of a cam fixed to the armature axle, and K is a condenser which is used here in an identical way to its employment in the induction coil. The metal casing of the magneto and engine constitutes the return circuit for the secondary and primary currents (Fig. 178 (*c*)).

Briefly the action of the magneto is as follows: With the contacts C closed, the rotation of the armature in the magnetic field of the permanent magnet will induce a current in the primary circuit, which will attain a maximum in a position approximately midway between (*a*) and (*b*) (Fig. 178). At this point the contacts C, actuated by the cam, are suddenly opened. Consequently a large e.m.f. is induced in the secondary circuit, causing a spark to pass between the platinum points of the plug. It should be noted by reference to Figs. (*a*) and (*b*) that there is an almost instantaneous reversal of flux when the contacts C are broken. In addition to the moving-coil type of magneto described above, there is a second type in which the coils are wound on a fixed iron core and a permanent magnet forms the rotor.

THE TELEPHONE.—The invention of this now familiar instrument is generally attributed to Graham Bell, in 1875, but he actually patented the device only a few hours ahead of a fellow American named Elisha Gray. A number of earlier experimenters (Bousseul, Reis, etc.) had constructed instruments by which sound of *constant* pitch could be transmitted, but Bell's apparatus was the first capable of transmitting *continuous speech.*

It should be remembered that during the production of sound waves, the air is being alternately compressed and rarefied. In other words the density of the air at any point in the path of the waves becomes alternately greater and smaller than the value corresponding to the quiescent state of the air. When these waves fall upon the drum of the ear the latter is set into vibration, and the sensation is finally

conveyed to the brain and interpreted as "sound." With these facts in mind, then the principle of telephonic transmission can be well expressed in Bell's own words: "If I would make a *current* of electricity vary in *intensity*, precisely as the *air* varies in *density* during the production of sound, I should be able to transmit speech telegraphically."

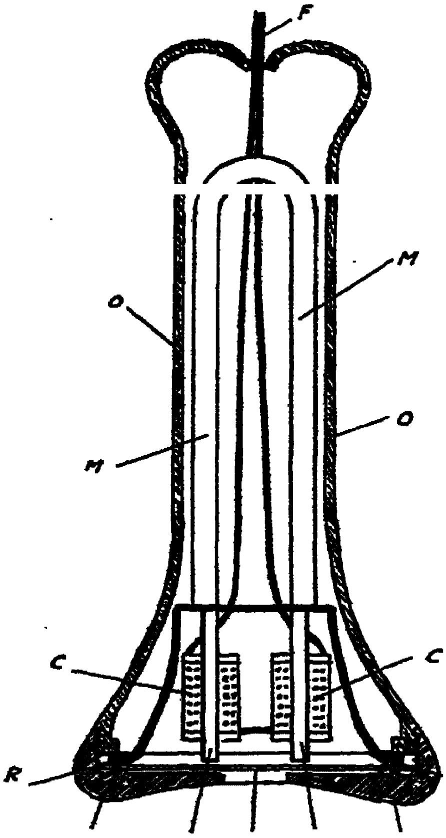


FIG. 179.

The construction of a typical modern magneto telephone is indicated in Fig. 179, but actually the design of the telephone *receiver* has not changed fundamentally from Bell's later instruments. The telephone consists essentially of a permanent cobalt steel magnet M fitted with two L-shaped soft iron pole pieces P, which are used to concentrate the magnetic flux. Two coils CC are wound on the pole pieces, and their leads pass through a hole in the upper end of the outside casing O. In telephony work these coils have a resistance of about 120 ohms, but for wireless purposes their resistance is usually 2,000-4,000 ohms. A circular disc of "stalloy" D is situated immediately in front of the pole-pieces and just behind the ear-piece (E). The periphery of this diaphragm D, as it is called, is clamped, by means of the ear-piece, to the rim R of an inner brass casing.

The above instrument may be employed as a *receiver* or *transmitter*, but nowadays it is almost solely restricted to the former use.

As regards its action as a transmitter it is obvious that on speaking into the ear-piece the diaphragm will vibrate, and by its to and fro movement will change the distribution of the magnetic flux cutting the coils C. Consequently the current induced in the coils and connected circuit (including a similar telephone acting as a receiver) will vary in a manner depend-

ent upon the vibrations of the diaphragm, which are in turn governed by the words uttered by the speaker. In the similar instrument used as a receiver the operations will be reversed. The fluctuations of the current in the line circuit will magnetise the pole-pieces to varying strengths, so that the pull on the diaphragm alters accordingly. The vibrations of the diaphragm will be communicated to the surrounding air so that the speech will be reproduced.

It should be carefully noted that if the receiver were not "*polarised*" (i.e. the permanent magnet is omitted) the diaphragm would be attracted twice in each cycle of the alternating current in the coils of the receiver, because the attraction would ensue whether a pole-piece is of north or south polarity. In consequence the pitch of the transmitted sound would be raised by one octave. With the use of the permanent magnet the pull is decreased and then increased in consecutive halves of each cycle, so that only one to and fro movement is made in the complete cycle. It can also be proved that the presence of the magnet increases the amplitude of the vibrations of the diaphragm.

By employing a telephone of this type at each end of a transmission line, one to act as transmitter and the other as receiver, Bell and Gray were able to work without the use of a battery. The distances of transmission, however, were comparatively small, but the range was extended to hundreds of miles by improvements in the transmission apparatus. A further improvement suggested by Edison, was the use of transformers (T) as indicated in Fig. 180.

The diagram shows the simplest circuit for use in long-distance telephony, and it involves, as can be seen, the separation of the transmitting and receiving sections. Now the loudness of the reproduction of the transmitted speech depends upon the *amplitude* (page 263) of the varying current, the *total* value of which is inversely proportional to the resistance of the whole circuit. But the *changes* in resistance only occur in the microphone (page 114), so that if this resistance becomes small in comparison with the total resistance of the circuit the *change* in current will be small, and hence the signals received will decrease in strength as the length of the "lines" connecting the stations is increased. In order to overcome this difficulty the arrangement is adopted (Fig. 180) whereby a battery B is included in series with a transmitting microphone

M, a switch S (to avoid any unnecessary use of the battery) and a low resistance primary coil of a small transformer T. When a transmitting circuit is closed and the " caller " speaks into the microphone, the diaphragm of the latter commences to vibrate and produces a fluctuating pressure on the carbon granules. The resistance of the granules, and therefore the primary current, varies proportionately to this pressure, and by electro-magnetic induction an alternating e.m.f. of the same frequency as the speech is induced in the secondary of the transformer T_1. In turn this e.m.f. will create a fluctuating current in the line circuit containing the secondary, and since the receivers (R_1 and R_2) are included in this circuit, their pole-pieces will become variably excited. It follows that the

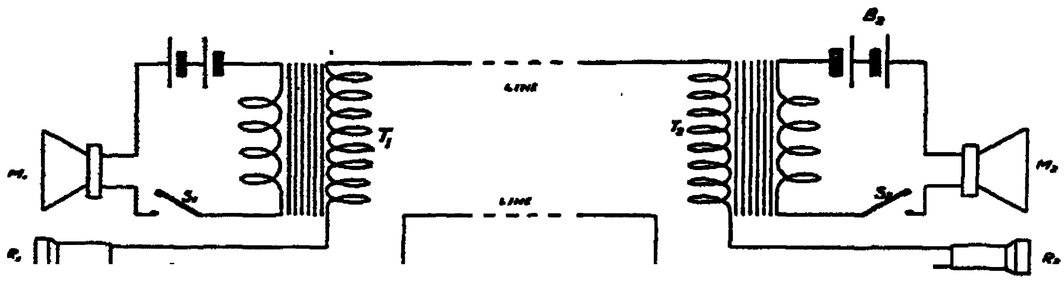


FIG. 180.

diaphragm of the receiver R_2 at the receiving station will generate sound waves of the same frequency as those uttered at the speaking station (M_1), and it is obvious that speech may be transmitted similarly in the opposite direction. An undesirable " interference " with the transmitted signals may occur if the telephonic (or telegraphic) lines run parallel to an " earthed return " system of electric traction. This induction effect will make itself evident as a buzzing in the phones, and will occur when there is any undue sparking at the current collecting contacts of the car, or in the motor system. In all modern telephonic lines a twisted metallic circuit is employed to overcome this trouble.

Rectification is the process of converting an alternating into a direct current. In addition to the mechanical method considered above, there is a type of *rectifier* which is dependent on the fact that a thin film of oxide on a copper plate offers a much higher resistance to the flow of current in one direction than in the other. These *metal rectifiers* have a wide field of application and can be arranged to give large

currents, for example 1,200 amps. at 12 volts, or smaller currents, say 1/10 amp. at 80,000 volts.

QUESTIONS.

1. State Faraday's Laws of Electro-magnetic Induction and describe one experiment to illustrate these laws.

Given a coil of wire and a galvanometer, how would you show that the earth is a magnet? (U.E.I., S1, 1932.)

2. State Faraday's and Lenz's laws of electro-magnetic induction. Calculate the average e.m.f. induced in a 1,250 turn coil when the flux linking with the coil changes from 20,000 to 50,000 lines in 0·0075 seconds. (N.C.T.E.C., 1934.)

3. Describe the construction, and with the aid of a diagram, explain the action of the induction coil. (U.E.I., S1, 1933.)

4. Define the Henry.

Explain what is meant by (*a*) self inductance, (*b*) mutual inductance. A coil has an inductance of 0·2 henry. When a direct current of 10 amperes flowing in it is reduced to zero at a uniform rate, an e.m.f. of 5 volts is induced. Find the time taken to reduce the current to zero. (U.L.C.I., B, 1935.)

5. Explain the principle of action of a transformer, and include in your explanation the reason why the primary current increases when the load on the secondary increases. (U.E.I., S3, 1932.)

6. An induction coil has a primary resistance of 5 ohms and should be used on 100-volt mains. If the supply is at 240 volts, explain what you would do to use the coil.

If the secondary current is 5 milliamperes, what is the highest voltage obtainable? (N.C.T.E.C., 1934.)

7. Make a sketch of a telephone transmitter and receiver. Explain the action of each part.

8. A tramcar travels at the rate of 35 metres per minute along rails which are 1·2 metres apart. If the vertical component of the earth's magnetic field is 0·4 gauss, find the e.m.f. between the ends of the rails.

9. Describe the fluxmeter and explain how you would use it to determine the pole strength of a bar-magnet.

10. It is desired to use a transformer to step-down from 210 to 4 volts. If the primary coil is wound with 1,200 turns, how many turns should be wound on the secondary coil?

CHAPTER XIV

THE DYNAMO AND MOTOR

It has already been shown (page 252) that when a conductor cuts a magnetic field an electro-motive force is induced in the conductor. The direction of this e.m.f. can be derived by applying Fleming's Right Hand Rule which is as follows: *Extend the right hand so that the thumb and first two fingers are at right angles to each other. Then if the* **F***irst (or fore) finger points in the direction of the* **F***ield and the thu***M***b in the direction of the* **M***otion of the conductor, the s***E***cond finger will give the direction of the induced* **E***lectro-motive force.*

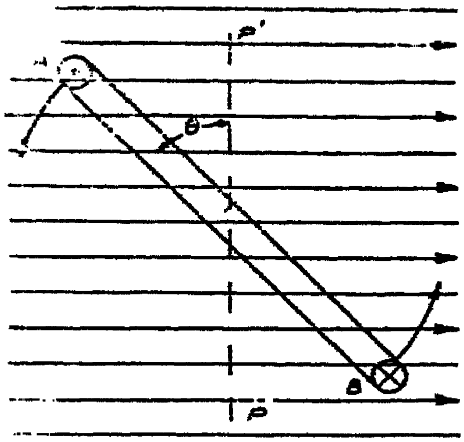
The right-hand rule applies to the dynamo, in contrast to the left-hand rule, which is applicable to the motor.

THE DYNAMO GENERATOR.—The name dynamo is given to a machine in which mechanical energy is converted into electrical energy through relative motion between conductors and magnets.

The dynamo in its present form consists essentially of two parts, viz. (1) the **field magnet** *system*, and (2) the *rotating coil or system of coils* which is called the **armature.** The latter usually consists of a number of copper bars which are insulated from each other and which are supported on an iron core. The core is introduced in order to increase the flux density through the armature. This clearly increases the induced electro-motive force.

COIL ROTATING IN A MAGNETIC FIELD.—Let ABCD (Fig. 181 (*c*)) be a coil which is rotated anti-clockwise about a vertical axis XY in the field of the magnet NS. A plan of the arrangement is shown in Figs. 181 (*a*) and (*b*). As the coil rotates the vertical conductors AD and BC cut the lines of magnetic force, so that by applying Fleming's Right-Hand Rule the direction of the induced e.m.f.'s can be ascertained. In Fig. 181 (*a*) it is evident that the induced e.m.f.'s act respectively in the directions DA, BC and furthermore it is easily seen that if the ends of the coil are connected, they will

assist each other to send a current round the closed circuit. When the plane of the coil reaches the position which is perpendicular to the plane of the paper (PP^1 in Figs. 181 (*a*) and (*b*)) the induced e.m.f. vanishes. On passing this position the direction of the induced e.m.f. in the circuit is reversed (see Fig. 181 (*b*)) and remains so until the plane of the coil is again perpendicular to the plane of the paper, when it becomes zero as before. If the rotation is continued the induced e.m.f. will now be in the original direction.



(*a*)

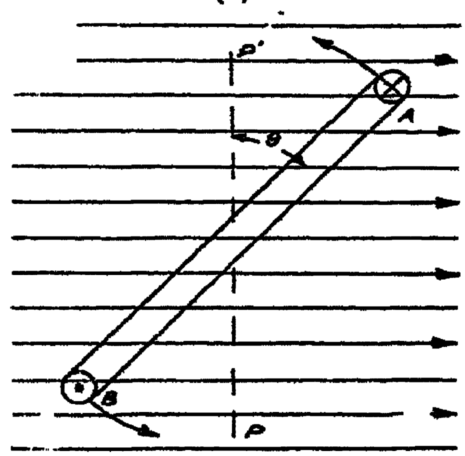


FIG. 181 (*b*).

The direction of the induced e.m.f. is thus reversed each time the coil passes through a position which is perpendicular to the plane of the paper. Its magnitude fluctuates between a maximum value when the coil is in the plane of the paper and the conductors AD and BC are moving at right angles to the lines of force, and a zero value when the coil is perpendicular to the plane of the paper and the conductors are moving parallel to the lines of force.

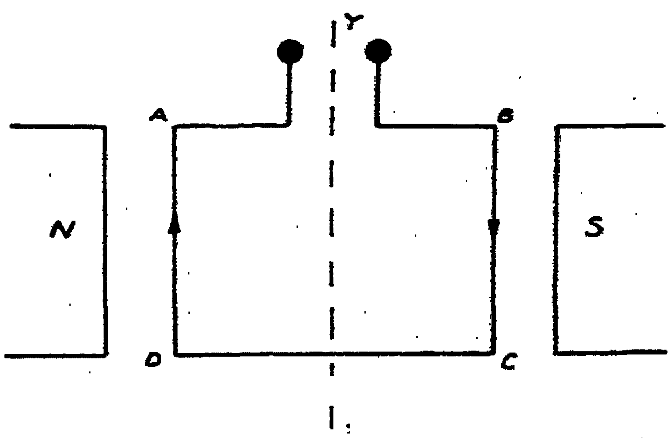


FIG. 181 (*c*).

If the coil is rotated about a horizontal axis then the above facts are still applicable, the induced e.m.f. being a maximum and a minimum when the coil is respectively horizontal and vertical.

It can be shown that the induced e.m.f. in the coil at any instant is proportional to the

sine of the angle that the plane of the coil makes with the perpendicular to the lines of force of the field. The **alternating** nature of the induced e.m.f. is shown in Fig. 182 where θ denotes the angular position of the rotating coil.

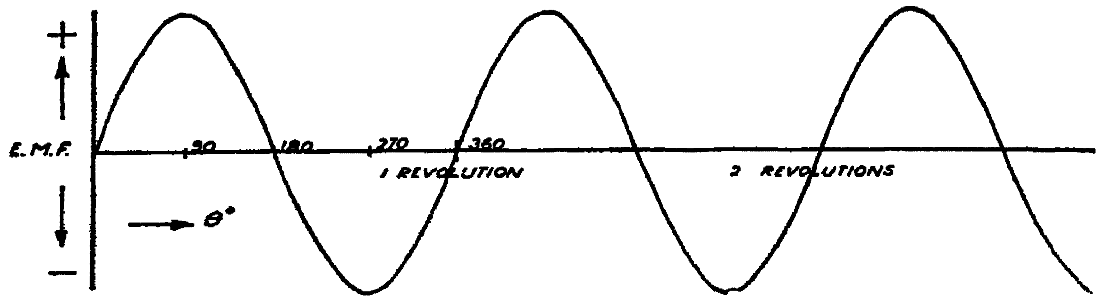
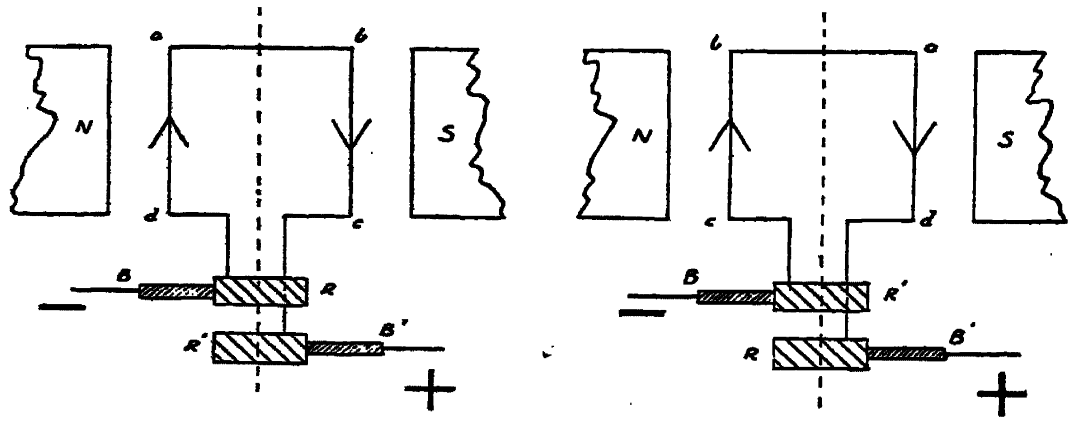


FIG. 182.

The dynamo is connected to the external circuit by means of *metal brushes*, and these make contact with two insulated *metal slip rings* which are permanently joined to the ends of the rotating coils. By the use of a *split-ring commutator* a current which is alternating in the armature coils is transformed into a direct current in the external circuit. The commutator consists of a split metal ring RR[1] (Figs. 183 (*a*) and (*b*)) the two segments of which are insulated from each



(*a*) FIG. 183. (*b*)

other. One end of the rotating coil is connected to one of these segments and the other end to the other segment. The brushes B and B[1] bear on the segments and convey the current to and from the external circuit.

The connections of these brushes are reversed at the same instant as the e.m.f. is reversed, so that the +ve end of the coil is always connected to the same end of the *external* circuit.

The current in the external circuit is thus unidirectional, so that the alternator is transformed, by the employment of a commutator, into a direct current dynamo. The current in the armature itself, of course, continues to reverse. Figs. 183 (*a*) and (*b*) show the direction of induced e.m.f.s in succeeding halves of the revolution of a coil *abcd* about a horizontal axis (dotted line in the Figures.).

ALTERNATING CURRENT (A.C.).—Fig. 182 shows a *sine* curve connecting the alternating e.m.f. and the angular

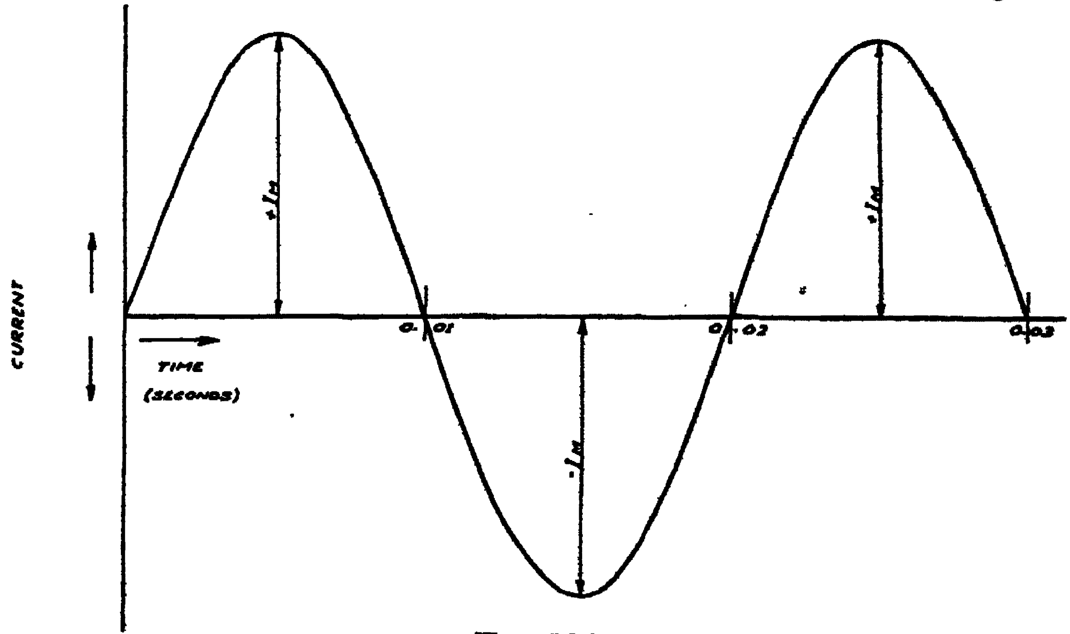


FIG. 184.

position of the rotating coil (page 262), and it should be evident that a precisely similar curve will indicate the relationship between current and time (Fig. 184). Referring to this latter curve the following definitions and terms are important.

The maximum *amplitude* I_m of the current is known as the **peak** (or **crest**) value.

A complete passage of current from zero to a +ve maximum, through zero to a −ve maximum and back again to zero is termed a **cycle**, and since this variation is regularly repeated the curve is said to be **periodic.**

In Fig. 184 it is seen that the period (T) of the cycle is 0·02 seconds, hence the frequency (*f*) or number of cycles per second $= \frac{1}{0{\cdot}02} = 50$. The frequency of most A.C. supplies is gradually becoming standardised at the above value. It

may be proved that the general expression for the instantaneous value (i) of the current at any time t secs. after its zero value, is given by $i=I_m \sin 2\pi ft$.

Example.—The maximum value of an alternating current is 20 amps. and the frequency is 50 cycles per second. Assuming that the variation of current obeys the sine law, determine at what time after the time of zero current, will the current attain half its maximum value.

$$\text{Here } I_m=20 \text{ amps.}$$
$$i=10 \text{ amps.}$$
$$f=50 \text{ cycles per sec.}$$
$$\therefore 10=20 \sin 2\pi ft=20 \sin 100\pi t.$$
$$\text{or } \sin 100\pi t = \frac{1}{2}$$
$$\text{But } \sin 30^\circ=\tfrac{1}{2} \text{ i.e. } \sin\left(\frac{30}{180}\times\pi\right) \text{ radians} = \frac{1}{2}$$
$$\text{Hence } \sin\left(\frac{30}{180}\times\pi\right) = \sin 100\pi t$$
$$\text{or } 100\pi t = \frac{30}{180}\cdot\pi = \frac{\pi}{6}$$
$$\text{i.e. } t = \frac{1}{600} \text{ secs.} = \mathbf{0{\cdot}0167 \text{ sec.}}$$

ALTERNATORS.—This term is applied to those machines which are used to deliver alternating current in an external circuit.

In these generators the magnetic field is *necessarily* excited by an auxiliary D.C. supply and as in the case of the dynamo the magnetic circuit is completed through the iron core of the armature. Now it has been seen previously (page 234) that the production of an induced e.m.f. is only dependent on the *relative* motion between the coil and magnet systems, and this fact is utilised in the design of alternators. These machines (in contrast to dynamos) are usually designed so that the *armature is fixed* while the field magnet system rotates *within* the armature. The armature and field magnet system are consequently often referred to as the **stator** and **rotor** respectively. One of the advantages of this arrangement is that with the higher voltages usually generated by alternators the problem of the better insulation which is

required is more easily overcome with a stationary, than with a rotating armature. The maximum voltage generated by these machines is limited in practice to about 15,000 volts, and to obtain higher voltages (e.g. for transmission) step-up transformers are utilised.

INTRODUCTORY FACTS ABOUT ALTERNATING CURRENTS.—It is not within the compass of this book to treat the subject of alternating currents in any detail, but a few simple experiments should be performed by the student, by way of comparison with the corresponding properties of direct currents.

The alternating character of the current may be conveniently illustrated by the following experiment:

Experiment.—Obtain a suitable carbon lamp and include it in a circuit where there is a D.C. source of the appropriate voltage. Show that the filament behaves as an ordinary current-carrying solenoid, by placing two opposing poles of a pair of bar-magnets in close proximity to the centre of the carbon filament. This " flexible " conductor will be seen to lengthen or contract according to the direction of the magnetic field and will remain so until the field (or current) is removed.

Repeat the experiment, using A.C. supply. The student will now observe that the filament is in a state of *vibration*, i.e. the lengthening and contraction are following each other in rapid succession, thus indicating that the direction of the current in the filament suffers reversal many times per second.

To show the effect of capacity (or capacitance as it is now termed) in an A.C. circuit the following experiment should be performed:

Experiment.—Connect up as in Fig. 185 (*a*) where C is a condenser of say 10 μFd. and L and B are respectively a suitable lamp and battery. G is a sensitive galvanometer. A momentary deflection of the galvanometer will be noticed, due obviously to a momentary current. This current will cease when the P.D. between the plates of the condenser is the same as that between the poles of the battery. This momentary current may be prolonged (and perhaps, therefore, made more evident to the eye) by the inclusion of a megohm in the circuit, since now the condenser will take a longer time to charge up.

Repeat the procedure (see Fig. 185 (*b*)) using the A.C. mains and a 40 or 60 watt lamp. This lamp will readily light up when C has a large value, say 5 μFd. or more. If the capacity

of the condenser is reduced to say 0·01 μFd. the lamp does not glow, for the quantity of electricity necessary to charge up the condenser through the lamp is now very small.

In a circuit containing capacity the current reaches its maximum value before the electro-motive force, and the current is said to *lead*. In the case of a circuit comprising an inductive resistance the current *lags* behind the e.m.f., since the self-induced e.m.f. always tend to oppose the rise or decay of the current in the circuit.

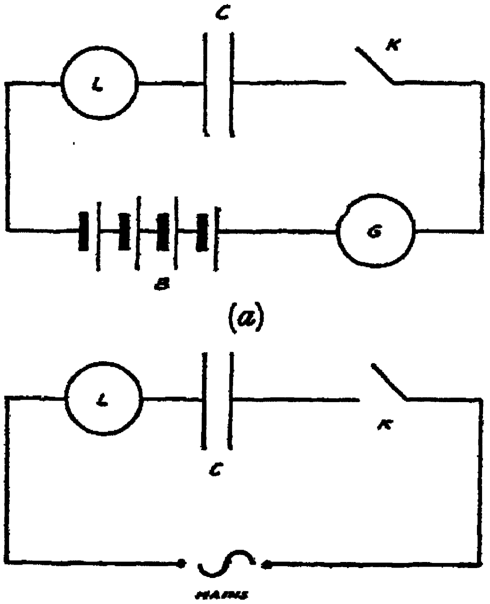


FIG. 185 (*b*).

The lag or lead between the current and impressed e.m.f. is known as the difference of *phase* between them.

It should be noted that it would have been useless to have included an ordinary galvanometer or moving-coil ammeter in the A.C. circuit above, for such instruments are unable to respond to such a rapid variation of the current intensity. In order to overcome this difficulty, use is made of the fact that both of the two following effects are independent of the direction of the current: (*a*) the heating effect of a current, e.g. the principle of the hot wire ammeter (page 139) and (*b*) the force between two coils carrying the same current, e.g. the principle of the wattmeter (page 140).

The magnitude of an alternating current is measured by the strength of the steady current which would produce the same heating effect as the A.C. current itself. Since the heating current is proportional to the square of the current at any instant it follows that this magnitude is given by $\sqrt{\text{Average Value of (Current)}^2 \text{ taken through a cycle}}$. This quantity is known as the **Root Mean Square** (R.M.S.) value of I, or its value in *virtual* amps.

It may be shown that $I = \dfrac{I_0}{\sqrt{2}}$ where I_0 is the maximum value of the current in the cycle.

Similarly the R.M.S. value of the voltage is

$$E = \frac{E_0}{\sqrt{2}} = 0{\cdot}707E_0$$

Where E_0 is the maximum value of the e.m.f. in the cycle.

The significance of the above remarks is made evident when it is noted that if a hot wire ammeter reads 10 amps. on an A.C. circuit, it means that the current (I) is actually varying between $+ I_0$ and $- I_0$, where $I_0 = 10\sqrt{2} = 14{\cdot}14$ amps.

The ratio of the voltage to the current in an A.C. circuit containing only capacity or inductance is known as the **reactance** of the circuit and may be measured in ohms.

In a circuit containing inductance (L) only the reactance is equal to $2\pi fL$, where f is the number of cycles per second, while in a circuit containing capacity (C) only the reactance is $\frac{1}{2\pi fC}$.

In an alternating current circuit containing resistance and inductance the expression for Ohm's Law becomes

$$I = \frac{E}{\sqrt{R^2 \times (2\pi fL)^2}}$$

The quantity $\sqrt{R^2 + (2\pi fL)^2}$ is known as the **impedance** of the circuit and it is evident that even if R is small the current flowing may still be reduced by increasing L. This arrangement has the further advantage of reducing the energy (I^2R) dissipated in the circuit, and in actual practice a device known as a "*choking coil*" is used to reduce or "choke" the current. This coil consists essentially of an inductive winding upon an iron core, the resistance of the winding being relatively small compared with its inductance.

The true power in an A.C. circuit is found by multiplying the apparent power (i.e. the product of virtual amps. × virtual volts) by a factor cos φ, which is known as the *power-factor* and whose maximum value is unity.

Skin Effect.—In A.C. supplies of large frequencies, say 500 or more cycles per second, the currents are confined chiefly to the surface of a conductor. This phenomenon is known as the *skin effect*, and besides depending on the frequency it is also proportional to the permeability and electrical conductivity of the wire. In fact for an iron wire the value of

the current in an A.C. supply of frequency 1,000 at 1/5 mm. below the surface is only about 1/10 of that at the surface. As a consequence hollow tubes will conduct as well as solid rods of the same external diameter. Litzendraht wire consists of many strands of insulated wire twisted together, and provides a low resistance to the passage of high frequency currents.

EDDY-CURRENTS.—It has been seen (page 252) that an e.m.f. is induced in a conductor, which is moved in a magnetic field or is subjected to a varying flux. Now from the point of view of electro-magnetic induction the shape of the conductor will be immaterial, but for a large body the induced e.m.f.'s in different parts may have different values owing to unequal changes of flux. It follows that as a consequence of the unequal magnitudes of these e.m.f.'s, induced currents will flow in *localised* paths within the metal.

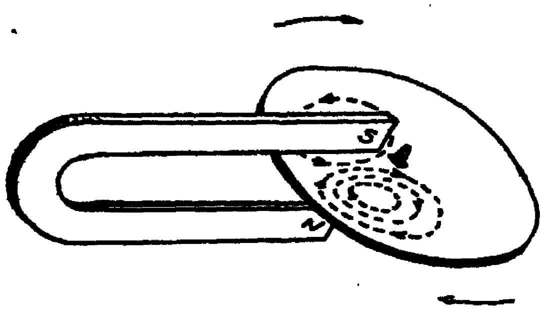


FIG. 186.

The direction of these eddy (or Foucault) currents, as they are termed, will be given by the right-hand rule and they will set up a magnetic field which tends to oppose the cause producing them. Hence if a copper disc is set spinning between the poles of a magnet as in Fig. 186 it will experience a mechanical drag (cf. a brake) which will quickly bring it to rest; alternatively if the disc is maintained in rotation it will become heated by the eddy-currents. This heating effect represents a loss of energy in the system, so that transformer cores, dynamo armatures, etc., are laminated to increase the resistance of the current-paths. Again the "braking-effect" is utilised in some forms of electric supply meter to control the speed of the moving system (page 231), and also in the damping of "hot-wire" instruments in which a disc fixed to the pointer moves between the poles of a magnet.

Experiment.—Obtain a short cylindrical magnet (a cobalt steel magnet about $2\frac{1}{2}$ in. long and $\frac{1}{8}$ in. diameter is very suitable) and place it in a stirrup attached to the lower end of a silk thread suspension, within an oscillation box (page 91). Carefully adjust the magnet to be horizontal and

approximately $\frac{1}{10}$ ins. above a horizontal cardboard disc (say 3 in. diameter), on which is marked a circular scale graduated in degrees. Deflect the magnet from its equilibrium position in a horizontal plane, note the maximum amplitude, say 60°, and count the *number* of oscillations before this amplitude is reduced to say 30°.

Repeat the experiment replacing the cardboard disc with a copper disc of the same size and thickness. Again count the number of oscillations made by the magnet before its initial amplitude is reduced by half, and it will be found to be much smaller than before. If a brass disc of similar dimensions to the above is available its *damping* effect on the motion of the magnet will be found to be intermediate to that of the cardboard and copper. This result is evident when it is considered that the damping effect is a function of the magnitude of the eddy-currents which in turn will vary inversely as the resistance of the material of the disc (when dealing with discs of identical size and shape).

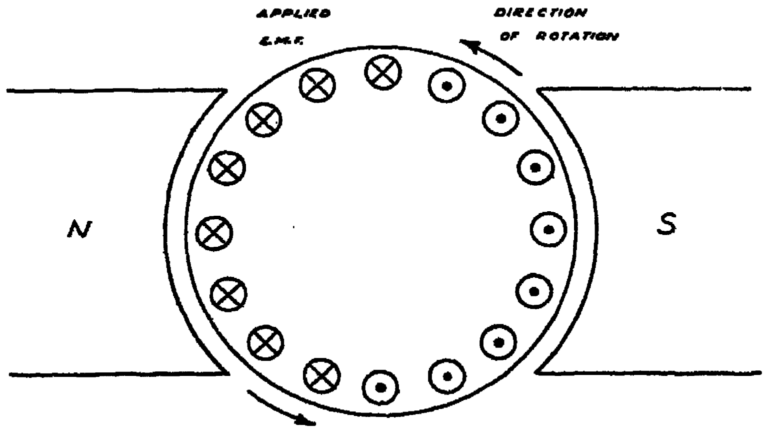
THE ELECTRIC MOTOR.—The electric motor does not differ in any fundamental point of construction from the dynamo. Its action, however, is the converse of the dynamo, for by means of the motor electrical energy is converted into mechanical work. The principle of the electric motor depends on the fact that a current-carrying conductor, placed in a magnetic field, experiences a force which tends to displace it across the field (page 72).

A number of simple rotating devices were invented following Faraday's discovery (1831) of the effect, but a Russian, Jacobi (1839), was the first to employ an electric motor in actual practice. He used a battery of about 60 large Grove cells to supply his motor, which was able to propel a boat on the River Neva at a speed of just over two miles per hour.

Referring to the case of the simple rotating-coil, split-ring, machine described on page 262, it is evident that if D.C. is led into the coil by one brush and out by the other, the coil will commence to rotate about a horizontal axis (see Fig. 183).

Further, this motion will be maintained if the brush contacts change from one slip-ring to the other when the plane of the coil is vertical. Again it should be clear, by applying the left-hand rule, that the direction of rotation will be reversed either by (1) reversing the e.m.f. applied to the brushes, *or* (2) reversing the direction of the magnetic field. It is also

obvious that the necessary reversals of current in the coil, to maintain continuous rotation, may be brought about by using an A.C. instead of a D.C. supply. In this case the alternations of current must occur at the correct moments, i.e. the motor must be running at the exact speed when connected to the A.C. supply, in order that its rotation should be maintained.



(a)

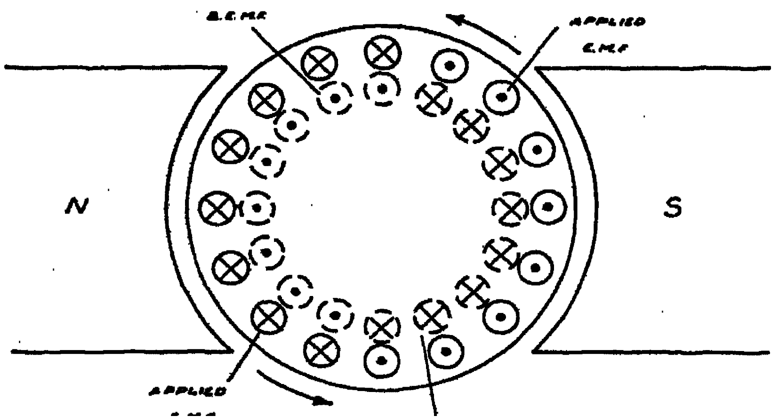


Fig. 187 (b).

Hence for a given frequency of supply these machines, known as **synchronous motors**, will only run at one speed.

The **torque** exerted by the above machine, i.e. the total turning effect of the electro-magnetic forces on the conductors, will vary continuously in magnitude between maximum and zero values, and to obtain a more uniform torque it is necessary to employ a larger number of conductors. Now the value of the torque is proportional to the current flowing in the armature, and hence it might appear that the speed of rotation

could be increased without limit by applying larger e.m.f.s to the armature. There is, however, another factor to be considered as will be evident if reference is made to the simple case shown in Figs. 187 (*a*) and (*b*). In Fig. 187 (*a*) the direction of the applied e.m.f. in the conductors is shown, and also the resulting direction of rotation of the armature. Now in consequence of this rotation in a magnetic field an e.m.f. will be induced in the armature conductors, and as will be seen, by applying the right-hand rule, its direction (Fig. 187 (*b*)) will oppose the applied e.m.f. (E).

Since this back e.m.f. (E_b) is proportional to the speed of rotation, the latter will increase until $E_b+I_A R_A=E$, where R_A is the armature resistance and I_A is the current flowing through it.

When the armature of a motor is stationary the back e.m.f. is obviously zero, and if a large e.m.f. is now suddenly applied, the current through the armature ($I_A=E/R_A$) may be excessively large, since R_A is generally quite small. For this reason a **starting resistance** or **motor starter** is connected in series with the armature. The whole of this resistance is initially in circuit so that the current is small at the beginning. By cutting out coils, one at a time, this current is gradually increased and in this way the speed of the motor is increased at a suitable rate.

QUESTIONS.

1. Describe briefly a simple method of producing an alternating current. Describe the comparative effects of passing (*a*) an alternating current, (*b*) a direct current through: (1) the coil of a tangent galvanometer, (2) a wire of high resistance.
Give brief reasons for your answer. (C. & G., 1935.)

2. Draw a diagram illustrating the main principle of the production of an electric current by a dynamo. Explain, with reference to any experiments, how a current is produced by a dynamo. (U.L.C.I., 1935.)

3. Explain the principle of action of the D.C. motor. Give sketches of the essential parts and name them. (U.E.I., S1, 1933.)

4. Explain the action of the commutator of a generator, illustrating your answer by sketches showing a coil of one turn rotating in a magnetic field and connected to a commutator consisting of two segments. (U.E.I., S1, 1932.)

5. What do you understand by (*a*) hysteresis loss and (*b*) eddy current loss, in regard to electrical machinery?

6. Write a short account of the properties of alternating currents by contrast with those of direct currents, and describe any simple experiments by way of illustration.

7. What do you understand by (1) a "choking coil," and (2) the "skin effect"?

APPENDIX

ELECTRICAL UNITS

Definition of Practical Units

Ohm.—The international ohm is defined as the resistance offered to an unvarying electric current by a column of mercury at 0° C., 14·4521 gm. in mass, of a constant cross-sectional area and of a length of 106·300 cm.

Ampere.—The international ampere is the unvarying electric current which, passed through a solution of silver nitrate in a specified manner, deposits silver at the rate of 0·00111800 gm. per second.

Volt.—The definition of the international volt follows from Ohm's Law (viz. international volt = international ampere × international ohm.) but it is also expressed by the E.M.F. of the Western Cadmium Cell, viz. 1·01830 international volts at 20° C.

Relations between Practical and C.G.S. Units

C.G.S. Electromagnetic Unit of Current	=	10 Amperes.
" " " Resistance	=	10^{-9} Ohm.
" " " Potential	=	10^{-8} Volt.
" " " Capacity	=	10^{9} Farads.
" " " Inductance	=	10^{-9} Henry.
C.G.S. Electrostatic Unit of Potential	=	300 Volts.
" " " Capacity	=	$\frac{1}{9\times10^{11}}$ Farads
" " " Quantity	=	$\frac{1}{3\times10^{9}}$ Coulombs

The following is a list of Greek letters employed in the text for denoting various electrical quantities :

α — alpha.	δ — delta.
θ — theta.	κ — kappa.
μ — mu.	ρ — rho.
ω — omega.	φ — phi.

Table of Symbols

Name of Quantity.	*Symbol.*
Temperature	θ
Frequency	f
Period	T
Potential Difference (P.D.)	V
Electromotive Force (E.M.F.)	E
Current	I
Quantity of Electricity	Q
Magnetic Field Strength	H
Magnetic Flux	φ
Magnetic Flux Density	B
Permeability	μ
Resistance	R
Capacity or Capacitance	C

Name of Quantity.	*Symbol.*
Dielectric Constant (or Specific Inductive Capacity)	K
Self-Inductance	L
Mutual-Inductance	M
Intensity of Magnetisation	I
Susceptibility	κ
Specific Resistance	ρ
Temperature Coefficient of Resistance	α
Angle of Dip	δ
Angle of Declination	D
Ohm	ω
Farad	F
Pole Strength	m

Prefixes and Symbols for Multiples and Sub-Multiples

m for milli denotes $\frac{\;}{1,000}$

μ for micro denotes $\frac{1}{1,000,000}$

M for mega denotes 1,000,000

k for kilo denotes 1,000

TABLE I

CONSTANTS OF ELECTRICAL CONDUCTORS AND RESISTANCE MATERIALS

Material.	Composition.	Melting Point (° C.).	Specific Resistance in microhms per cm. cube at 20°C.	Mean Temperature Coefficient of Resistance per degree C. Range 0°C–100°C. approx., unless otherwise stated.
Aluminium, drawn	—	655	2·95	0·0038
Carbon, moulded electrodes	—	3,400	3,000–7,000	—0·0006 to —0·0012
Constantan (or Eureka)	60% Cu, 40% Ni	—	49	—0·00004 to +0·00001
Copper, annealed	—	1,091	1·724	0·00428
Copper, hard drawn	—	1,091	1·793	0·0040
German Silver	60% Cu, 15% Ni, 25% Zn	—	20–35	0·0003 to 0·0006
Iron pure	—	1,515	9·8	0·0062
Kanthal	—	—	145	0·00006 (20° C. to 900° C.)
Manganin	84% Cu, 4% Ni, 12% Mn	—	44·5	0·000002 to 0·00005, Average ·00001. Zero coefficient from 30° C. to 40° C.
Mercury	—	—38·8	95·77	0·00089 (0° C.–25° C.)
Nichrome	—	—	110	0·00017
Nickel (Commercial)	—	1,450	10·5	0·004
Nomag	—	—	140	0·0009
Phosphor Bronze	92·5% Cu, 7·0% Sn, 0·5% P	—	7–8	0·002 to 0·004
Platinoid	62% Cu, 15% Ni, 22% Zn, 1% W	—	35–45	0·00023
Platinum	—	1,710	11·1	0·0037
Silver	—	960	1·62	0·0040
Tin, drawn	—	232	11·4	0·0044
Tungsten, drawn	—	3,300	5·8–6·2	0·0057 (0° C.–900° C.)

Cu = Copper   Mn = Manganese   Ni = Nickel   P = Phosphorus   Sn = Tin
W = Tungsten   Zn = Zinc

ELECTROCHEMICAL EQUIVALENTS (E.C.E.'s.)

(in milligrams per coulomb)

Hydrogen . .	0·0105	Silver . .	1·1180
Oxygen . .	0·0829	Lead . .	1·0731
		Copper . .	0·3294

1 coulomb decomposes 0·09334 m.gm. of water.

E.M.F.'s. OF CELLS

Approximate E.M.F.'s of Primary Cells on Open Circuit.

Léclanche . . .	1·5 volts.
Daniell	1·1 volts.
Bunsen	1·9 volts.

WESTON STANDARD CADMIUM CELL

E.M.F. at 20° C. = 1·01830 volts.

Note.—The maximum permissible current from a standard cell without perceptible polarisation is about 5×10^{-5} amp.

TABLE II

DIELECTRIC PROPERTIES OF INSULATING MATERIALS

Material	Specific Resistance in megohms per cm. cube.	Dielectric Strength, i.e. Breakdown Voltage, in kilo-volts per cm.	Dielectric Constant or Specific Inductive Capacity.
Amber . . .	5×10^{10}	—	2·86
Bakelite moulded .	$(1\text{-}40) \times 10^{6}$	100–200	2·5 – 5·0
Ebonite . . .	2×10^{9}	270–400	2·0 – 3·5
Glass . . .	10^{3}–10^{6}	60–500	5·0 – 9·0
Gutta-Percha . .	10^{7}–10^{9}	80–200	2·5 – 4·0
Mica . . .	10^{8}–10^{11}	500–3000	5·0 – 8·0
Mycalex . . .	10^{7}	120	6·1
Paper (including varnished) .	10^{4}–10^{8}	60–400	2·0 – 4·0
Paraffin Wax . .	10^{10}–10^{12}	100	2·0 – 2·3
Porcelain . . .	10^{7}–10^{9}	80–120	4·5 – 6·5
Presspahn . .	10^{4}	80–160	2·5 – 5·0
Quartz . . .	10^{8}	—	3·5 – 4·5
Rubber (vulcanised) .	5×10^{9}	120–240	3·0 – 5·0
Sulphur . . .	10^{10}–10^{11}	—	3·0 – 4·0

TABLE III

MATERIALS FOR PERMANENT MAGNETS

Material.	Coercive Force in oersteds.	Remanence Induction in gauss.	Maximum useful energy in ergs per cc.
6% Tungsten Steel	60–70	10,000–12,000	11,000
15% Cobalt Steel	185–195	7,800–8,300	26,000
35% Cobalt Steel	220–250	8,500–9,500	38,000
"Darwin-Alni"	400–650	5,000–7,000	50,000

"Darwin-Alni" (an alloy containing Ni and Al) remains stable up to a temperature of 500° C.—600° C., whereas Cobalt and Tungsten Steels are limited in use to temperatures below 300° C. and 150° C. respectively.

NOTES ON MATERIALS FOR CORES OF ARMATURES, TRANSFORMERS, ETC.

The desired characteristics of these materials are in general high permeability, high saturation density, small hysteresis loss and high electrical resistance. Swedish iron (maximum permeability 3,000) was formerly used for cores but there are alloys, e.g. Stalloy, Lohys, etc., containing small percentages of silicon or aluminium, and which show greatly enhanced values of maximum permeability (up to 8,000), and a reduced hysteresis loss. More recent alloys of Nickel and Iron, e.g. Permalloy and Mumetal have initial values of permeability of 20,000 and maximum values of 90,000. These materials are ideal for magnetic shielding against stray flux, gramophone "pick-ups," moving-iron instruments, and for submarine cable "loading," in which a sheath of soft iron is employed to ensure clearness in high speed signalling.

ANSWERS TO NUMERICAL PROBLEMS

CHAPTER I

3. $1\cdot75$ dynes.

10. $1\cdot442$ c.g.s.

11. $2\cdot571$ c.g.s.

CHAPTER II

5. (*a*) 4 dynes repulsion.
   (*b*) 16 dynes repulsion.

CHAPTER III

3. (*a*) $2\cdot4\mu F$.
   (*b*) $10\cdot0\mu F$.

5. (*a*) 10^{-3} coulombs.
   (*b*) $0\cdot7541 : 1$.

7. $\dfrac{10\cdot42}{d}$ e.s.u.

   $\dfrac{1\cdot30}{d}$ e.s.u.

8. (i) $10\cdot0$ e.s.u.
   (ii) $1\cdot11\times10^{-5}\mu F$

10. $1\cdot972\times10^{-3}\mu F$.

CHAPTER IV

1. 55 volts.

CHAPTER V

3. $8\cdot66$ secs.

4. $603\cdot0$ c.g.s.

CHAPTER VI

1. 0·0533 amps.
   2·67 volts.
2. (i) 3 amps ; 1·5 amps.
   (ii) 2 amps ; 1·0 amps.
3. (i) in two parallel groups.
   (ii) cells in series, current =2·4 amps.
   (iii) cells in parallel grouping, current =3·0 amps.
4. 0·0129ω.
5. 179·0ω.
6. 4·5ω.
   20·0 amps.
7. 25.
8. 7.
9. $\frac{1}{18}\omega$ i.e. 0·0556ω.
10. 24,500ω.
11. (*a*) 859·4.
    (*b*) 4·815 amps.
12. (*a*) 192 lines.
    (*b*) 76,800 lines.

CHAPTER VII

2. 252·0 calories.
3. $2{\cdot}843 \times 10^5$ calories.
4. 1·984° C.
5. (*a*) 14·4 pence.
   (*b*) 10·0 pence.
6. 201·67ω.
   10·8 pence.
7. (*a*) 9·0 amps.
   (*b*) 18·0 pence.
8. (i) 1·5ω.
   (ii) $\dfrac{\text{Heating Effect in } 3{\cdot}0\omega}{\text{Heating Effect in } 1{\cdot}5\omega}=\dfrac{1}{2}.$
9. 21 mins. 57 secs.
10. (i) 1·575 B.O.T.
    (ii) 5,444 B.Th.U.
11. 0·21 pence.

CHAPTER VIII

4. 0·1315 amps.
7. Silver 894·5 coulombs.
   Copper 3,049 coulombs.
   Hydrogen 96,160 coulombs.

CHAPTER IX

6. (i) 85·0%.
 (ii) 72·1%.

8. (i) 40 amps.
 (ii) 2·50ω.

CHAPTER X

1. 5·0ω.
 0·015 amps.

2. 0·0802ω.

3. 300·0ω.

CHAPTER XII

7. $9 \cdot 0 \times 10^{-4}\omega$.

8. 21·88ω.

9. 2·0ω.

10. (i) 4ω.
 (ii) 8ω.
 (iii) 3·75 amps.

11. 146·5 cms.

CHAPTER XIII

2. 50 volts.

4. 0·4 second.

6. (i) insert a resistance of 7ω in series with the coil.
 (ii) 400,000 volts.

8. $2 \cdot 8 \times 10^{-5}$ volts.

10. 22·8.

INDEX

Q

R

S

THE LONDON AND NORWICH PRESS, LIMITED, ST. GILES WORKS, NORWICH